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Compliments of the
Hawaiian Volcano Observatory

SECOND
REPORT OF THE HAWAIIAN VOLCANO OBSERVATORY

OF THE MASSACHUSETTS INSTITUTE
OF TECHNOLOGY AND THE HAWAIIAN
VOLCANO RESEARCH ASSOCIATION

T. A. JAGGAR, DIRECTOR

ON CYCLICAL VARIATIONS IN ERUPTION AT KILAUEA

BY HARRY O. WOOD

PUBLISHED BY THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY, CAMBRIDGE, MASS.

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PREFATORY NOTE

This work treats chiefly of observed changes in the height of stand of molten lava in the crater of Kilauea. It also takes account of concurrent variations in the apparent energy of eruptive action at the surface of the magma column. With little doubt these conditions vary in a complex periodic way.

To explain these periods in part an hypothesis is advanced which depends upon recurrent astronomical changes. It would be exceedingly difficult to develop this in any thorough dynamical way. Yet it is doubtful if any other treatment could serve quite adequately. Obviously the form given it in this study is crude.

In ordinary language it is not easy to state the idea precisely, so as to differentiate the exact action hypothesized from action of a similar and familiar kind. Consequently such a presentation of the hypothesis as this is susceptible of erroneous comprehension. Besides, through incompleteness, this non-mathematical statement of it may be wrong in certain aspects or details. Therefore this paper must be read guardedly and with close attention.

During the whole progress of the study the writer has had no access to adequate scientific reference libraries.

Notwithstanding its deficiencies the hypothesis tends to clarify a confusing group of phenomena. So it is put forward with apologies for its want of thoroughness. And, in full knowledge of its weaknesses, it is stated in a positive and assertive form to avoid wearisome iteration of qualifying words and phrases.

Whatever the fate of the hypothesis, the observations assembled are of much significance and deserve the attention of a larger circle than has learned of them hitherto. The writer has found it a confusing task to attempt their presentation in the absence of a guiding idea. This must be the justification for the form given to this study.

While assuming full responsibility for the publication of this work, and for all its shortcomings, the writer gratefully acknowledges helpful criticisms, — some favorable, others adverse, — and many constructive suggestions which have led to marked improvement in the presentation received from Professor A. E. H. Love, Sir Joseph Larmor, Professor T. C. Chamberlin and Professor F. R. Moulton.

He is especially indebted to Professor H. F. Reid, who went over an early draft with great care, and to Professor T. A. Jaggar, Jr., who has followed the work in all its stages. In making these acknowledgments it is only just to add that certain of these gentlemen are not wholly convinced of the adequacy of the hypothesis put forward here. And none of them may be charged with any responsibility for any errors or deficiencies in it.

I. INTRODUCTION.

History and Character of the Variation.

According to fragmentary information, for many years previous to the end of 1894 at least one "lake" of molten lava, commonly more, could be seen in the central region of the great crater of Kilauea, — save for widely separated intervals of short duration. Indeed, from the time the crater was first observed, in 1823, down to 1894 only a few brief interruptions of this phase of the activity of the volcano are known to have occurred. During a great part of this long term the molten lava frequently had welled over the banks of the pits, or "lakes," in which it was confined and streamed away over the adjacent crater floor. In this way the large inner depression of the great Kilauean sink gradually filled until, at length, a low, flat cone came to be built where in 1823 there had been a great, deep pit. Thus the entire floor of the great crater eventually was built up to higher levels.

In July, 1894, in conjunction with a series of light, local earthquakes, this phase of nearly continuous activity suffered an unprecedented check. The surface of the molten lava fell rapidly to a great depth in the Halemaumau pit, to which it had become confined; it did not afterward recover its previous high level; and in December, 1894, it sank out of sight altogether. By inference this has been attributed to a submarine outflow, but there is no proof of this in evidence.

Thereafter on several occasions molten lava reappeared at the bottom of the Halemaumau pit, but in each instance it was visible for only a very short time until, in 1906 or 1907, the volcano resumed the continuously active condition. From then until the first of May, 1913, molten lava was visible in Halemaumau practically at all times.

Thus the volcano was relatively dormant from 1894 to 1907. It was this long period of subordinate activity that was without historical precedent. As we shall see, this dormant interval affords valuable information in relation to the hypothesis here advanced.

About the first of May, 1913, the molten lava, which had been subsiding gradually, again fell from sight into the depths beneath the central region of Halemaumau. But it soon reappeared, in October, 1913, in spatter cones, boiling pots and areas of overflow, at the bottom of the pit, where it slowly built its surface to higher and higher levels in a fluctuating way until in October, 1914, the phase of a molten "lake" was resumed again. Since then, up to the date of writing this condition has prevailed, — with fluctuations in the height of stand and the vigor of surface action.

In connection with the present study it is noteworthy that, while the surface of the molten magma has been visible practically at all times throughout these two later, active periods, the lava has not once overflowed the rim of the Halemaumau pit in which solely it has been confined.

Nor is there reason to think that there has been any *spasmodic* subterranean drainage of large amount from the Kilauea magma reservoir during this time, as was the case, perhaps, in 1894.

This is in marked contrast with the behavior during the long former interval of continuous activity.

For these later intervals, then, covering with the one short interruption the eight years, 1907-1915, the molten surface has visibly risen and fallen in the single, central pit — somewhat as that of mercury in a barometer tube — a veritable though rather crude registering meter of the resultant of the lifting forces at work upon the magma column.

Throughout these more recent active times the volcano has been very often under casual observation. Visits by travelers and by residents of the Islands have been frequent. Also during the entire time the volcano has been under the eye of one man, Mr. D. Lycurgus, manager of the hotel at the brink of the main crater, whose business interest has required him to have tolerably accurate information as to the spectacular phases of the activity. Moreover, a considerable number of scientific men have made visits to the crater, and for the past four years, with one brief interruption, resident workers in vulcanology have been conducting routine observations.

Consequently, during this eight-year interval there have been relatively few weeks, more recently very few days, in which the scene has gone unobserved. No spectacular conditions have escaped notice.

Since 1906 it has been conspicuous that the magma surface has been high, and the surface action notably great, on several occasions in the June-July and the December-January parts of the year, while, conversely, relatively low and inactive stages have been noted usually in the September-October and the March-April seasons. The routine vulcanological work of the past four years tends strongly to indicate this. Indeed, it is the consensus of all available observations that, throughout these later eruptive intervals, there has occurred a semi-annual variation in the behavior of the magma column — with relatively high stand and augmented activity near and following the solstices and relatively low stand and diminished action near and after the equinoxes. Such a tendency was recognized independently by several persons, among these Mr. Lycurgus. Also it is noteworthy that Green,* though it does not appear that he recognized or referred to such a variation in observed action, long ago strongly emphasized the point of augmented earth-strain at time of solstice.

During the earlier long term of nearly continuous activity, the action at Kilauea was observed very irregularly and meagrely. And the comments of many of the visitors then are rhetorical and vague as to specific condi-

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*Vestiges of the Molten Globe, Part II, pp. 37-39, 242.
Wm. Lowthian Green, Honolulu, 1887.

tions. Also in those years the molten lava overflowed its basins frequently, or broke through their congealed embankments, so disturbing the barometer-like balance of conditions which has prevailed more recently. Nevertheless there is noted a *tendency* for the maximum eruptive phases to occur early in summer or in winter, and for times of relative quiet to occur early in spring or fall. However, referred to this vague and meagre record, during an interval when overflowing was frequent at all times of year, the correspondence between observed volcanic activity and the semi-annual astronomical period is less obvious during this term than in the later intervals.

In addition to the semi-annual variations in the manifestations of eruption, there has been much fluctuation in lesser degree in the height of stand and in the amount and variety of surface action in the course of the year. It has been considered by the vulcanologists working at Kilauea that in an approximate way these fluctuations have followed the lunar cycle. This also was noted independently by Lycurgus, who thought of it in relation to the *phases* of the moon, and much earlier by Lyons,* who considered the relation in causal terms.

These changes, however, have not conformed in any precise way to quadrature or syzygy, nor to apogee or perigee. Nevertheless the correspondences have been such in degree and kind as to emphasize the probability that variations in lunar forces are prominent factors in producing these fluctuations in volcanic activity.

Further, there appears to be a cyclical variation in the eruptive phenomena, with a period of several years, which seems of still greater amount than that which takes place during the half-year. For reasons which will be clear at a later stage of the study, the writer is much inclined to the testing of a hypothesis that this variation follows strain changes arising from the changes in earth configuration which accompany the cycle of free nutation due to variation of latitude.

Of course it is recognized clearly, even emphatically, that many other important forces are in play, — accumulating tectonic stresses, varying potential due to chemically unstable conditions in the depths, gas disengagement and evolution at and near the surface with chemical interaction and the development of heat, etc. Some of these may dominate the *major*

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*In an interview in a Honolulu newspaper in the summer of 1902, Curtis J. Lyons, then Government Meteorologist of the Hawaiian Islands, stated:

". . . it is known that the crust of the earth is more or less plastic, and it would be likely in that case to feel the force of attraction of the sun and moon. This force of attraction varies as the earth turns on its axis and thus produces a stress upon the materials of the earth's crust. . . .

". . . In the eruption of 1880-81, when the lava was flowing from Mauna Loa toward Hilo, and the front end of the flow was many miles from the source, upon Mauna Loa, it was noticed that the stream would sometimes come to an entire standstill and then break out with renewed vigor at intervals. These were intervals of about a month. I noticed that they also came at about the time of the new moon. . . . "

(Mr. Lyons predicted one of these rejuvenations of flow successfully.)

". . . That was what set me to thinking about the effect of this gravitation. I am inclined to attribute the precipitation of volcanic action very largely to this 'stress of gravitation' as I call it."

(In this interview Lyons also discussed sunspots and their relation with volcanic activity in Hawaii and elsewhere. He pointed out also the greater attraction at perigee.)

eruptive action of the volcano, indeed, very likely do dominate its secular behavior.

Nevertheless, the observations in hand strongly indicate definite, short-term, cyclical variations in the action at Kilauea, which are parallel with well-known solar and lunar cycles, and are likely produced by concomitant, periodic, gravitational distortions of the body of the earth.

Two of these correspondences have been pointed out in the local press — and possibly elsewhere before this — by Perret, the well-known vulcanologist, who was stationed at Kilauea in 1911 from July to October; and later by Jaggar, stationed at Kilauea since early in 1912, both of whom, on such an astronomical basis, have made generalized predictions of the behavior of Kilauea, and of Mauna Loa also, with signal success.

II. HYPOTHETICAL CONSIDERATIONS.

CRITIQUE OF PERRET'S LUNI-SOLAR FORCE CURVE.

This is not an appropriate place for a general review of attempts to correlate periodic terrestrial phenomena with astronomical cycles. But one of these efforts requires attention here. Perret,* in 1908, after much observation of volcanic and seismic phenomena in Italy, constructed a time-curve designed to express qualitatively the variation in the luni-solar force tending to distort the earth. In constructing this curve he took into account,

(1) changes in the distance of the moon from the earth (but he took no account, explicitly at any rate, of changes in the sun's distance),

(2) changes in the angle subtended between the moon and the sun from the earth as a vertex (or rather, to simplify the work, the positions of quadrature and syzygy),

(3) changes in declination with respect to the earth's equator (but whether of the sun, or of the moon, or of both bodies concurrently, is not very clearly stated, — presumably of both bodies, however.)

To each of these factors Perret assigned arbitrary numerical values based on his vulcanological experience — for precise gravitational equivalents are not in accessible, practicable form. Combining algebraically his arbitrary values for these factors he built up a curve which indicates a variation from day to day in a luni-solar earth distorting force. This is a crude sine-form curve, with irregularly unequal crest and trough ordinates, which has an interval of half the lunar cycle, about a fortnight, between corresponding phases. The mean of this curve exhibits a semi-annual period, but of much smaller amplitude than that of the fortnight.

Though in some critical sentences his exposition is wanting in explicitness, nevertheless it is clear that this curve expresses chiefly the variation from epoch to epoch in the value of a

diurnal, earth-tide-producing force,.

that is, a force which would tend to set up in the earth's body a diurnal, travelling wave the height of which must vary from day to day, through month and fortnight, year and half-year, as the strength of the luni-solar force producing it varies. For in the construction of the curve Perret gave ***predominant weights*** to

(1) considerations as to quadrature or syzygy, and

(2) considerations as to the moon's distance — giving subordinate weight to

(3) considerations of the declination angles of sun and moon.

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*Science, August 28, 1908.

Notwithstanding this, regarding the *action* of this force, he very emphatically says:

> ". . . but we should avoid considering this influence on the basis of tidal action, — it is because of this, in my opinion, that much misunderstanding has arisen. We have not to do with a liquid ocean, where, under luni-solar attraction, a moving wave-form would produce, at the time of maximum effect, very high and very low tides, but we must consider a mosaic globe, comprised for the most part of solid materials in which the effects, though not of such amplitude as to be visible, will be more powerful and less ephemeral. We may imagine the mean luni-solar effect upon the earth during the several days of each favorable position to be a tendency to positive deformation of the sphere."

With certain aspects of this view of Perret's the present writer concurs. With regard to the mechanics of the action he thinks it reasonable that the rigid earth, enveloped by a broken, crustal mosaic, might tend to modify the working of the earth-tide somewhat as suggested. However, this view has not found unqualified acceptance. And, in any case, the writer considers that the more dominant volcanic variations are better explained by a different mechanism which is discussed below.

Nevertheless, taking *lag* into account, and considering that readjustments take place under action of terrestrial gravity among the blocks of the earth's crustal mosaic at times indicated by the troughs of his curve (periods of neap-earth-tide configuration), — crust blocks whose mutual adjustments have been disturbed by positive, gravitational deformation at times indicated by the crests of his curve (periods of spring-earth-tide configuration),— Perret has found his scheme of service in interpreting and predicting volcanic and seismic behavior.

However, in attempting to employ this scheme in a consideration of Kilauean data — assuming causal correspondence between the astronomic cycles and the variation in volcanic action — the present writer was struck by two outstanding tendencies which seem to him to be important departures from strict correspondence with such an earth-tide force-effect, with probably a third departure also, as indicated below.

Here, as Perret recognized and as he would expect in some degree, instead of conspicuous, up and-down, diurnal movements of the magma surface at certain epochs with less marked diurnal rise and fall at intervening times, all referred to a constant mean level or to mean levels which undergo only slight semi-monthly and very slight semi-annual variations — we recognize a quite different behavior. Diurnal variations parallel with the diurnal body-tides, — though suspected, — if they exist definitely must be demonstrated by more refined and more frequent observations than have been undertaken as yet. The outstanding noteworthy circumstance, already pointed out, is a condition of prolonged high stand of magma with increased activity at and after *both* solstices (though one just precedes aphelion, the other perihelion) which gradually subsides to, and thereafter rises from, a state of prolonged low stand with reduced action around equinox and mean solar distance. Superposed upon this at all seasons is a lesser fluctuation in altitude and activity which appears to follow the lunar cycle in a similar gradual manner.

These are two of the more conspicuous variations in activity at Kilauea.

Whence we see that — though Perret anticipates from his view of the mechanics of action *gradual* rather than *diurnal* responses to the earth-distorting force — above all

(1) an action of the **sun** is apparently far more potent than any of the moon in producing uplift and sustained high level of the magma surface; and

(2) the **declination** of the sun, both summer and winter, not its distance from the earth, seems to control its most marked apparent effect upon the column.

Wherefore, by analogy, it is possible that

(3) the declination of the moon, instead of its distance or phase, may be the chief controlling factor in producing the minor fluctuations which appear to follow gradually through the lunar cycle.

In any case, considerations of quadrature and syzygy are necessarily quite subordinate in reference to the greater, solar cycle, if not in regard to the lesser, lunar cycle.

Now, as the writer understands it, the longer and greatly predominant volcanic fluctuation does not correspond with any conspicuous, explicit properties of the Perret curve, but can be referred to it chiefly by a process of subjective interpretation of its meaning which, while an entirely legitimate use of the curve, is a procedure which might lead to confusion of understanding.

Consequently it is considered that the force which acts to produce the diurnal body-tide in the earth, or an earth-distorting force which varies in amount approximately as that expressed by Perret's curve, cannot predominate *through any primary mechanism* in controlling this Kilauean behavior. For in such a force the moon's influence is greater than that of the sun, and conditions of quadrature and syzygy are of more weight, probably, than the angular declination of the bodies. This certainly is so constructively in the case of the Perret curve.

Recognition of this predominant effect of the solar declination, and presumably of the lunar declination also, in influencing the volcanic phenomena led the writer to the following hypothetical consideration of the mechanisms of its action and, thence, to a correlative review of available observations bearing on the variations in volcanic activity here.

III. HYPOTHETICAL CONSIDERATIONS (*continued*)

ON MECHANISMS AND CAUSES FOR THE VOLCANIC FLUCTUATIONS.

It is a fundamental thesis in this study that the rise, and fall, of magma in Halemaumau are chiefly manifestations of very minute variations in the volume of the magma reservoir. Nothing is postulated as to the shape of this, but it is considered that even extremely small changes in the volume of its whole, relatively enormous body would be integrated into a pronounced movement of uplift or subsidence of the free surface of the melt in conduits of relatively insignificant bore such as lead to the earth's surface. This interpretation is complicated by circumstances that will be touched on later. But such is the broad consideration from which this study starts. Thus the problem becomes — what forces produce these volume changes and how do they act and vary?

We seek to understand and explain effects which exhibit half-year periods, half-month periods, and effects, probably of greater magnitude, which have periods of several years. These obviously suggest astronomical cycles.

In what follows it is difficult to write clearly for geological readers, to whom along with all interested in geophysics, the study is mainly addressed, without making the presentation of more elementary character than is required for astronomical readers and others of superior training in dynamics. A treatment clear to all qualified readers is manifestly needed.

THE TIDES AND THEIR EFFECTS.

It is commonplace knowledge that changes in the distances, relative positions and declinations of the sun and moon with respect to the earth and its equator bring about progressive changes in the gravitational potential which raises the tides in the sea and deforms the body of the earth in a tidal way. Besides the semi-diurnal tides produced by this potential, in consequence of the earth's rotation, changes in its amount and direction bring changes in the gross amount of the tidal responses, and in the geographical location of the maximum effects, so that *semi-monthly* and monthly, *semi-annual* and annual variations in the amounts of the daily tides are found in all places.

These tides, being due to gravitational potential acting upon earth particles at differential distances during the rotation of the earth, do not depend (except as to their precise development)* upon the earth's *precise* shape, — they would result, for example, though in different amount and ways, if the earth were strictly spherical instead of being an irregular, or possibly pearshaped, spheroid, or if it had a still more irregular shape. This fact is of basic importance in developing the present hypothesis. We soon come to it again.

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*Cf. Vestiges of the Molten Globe, Part II, Appendix to Chap. I, p. 229. W. L. Green, Honolulu, 1887.

DIRECT TIDAL EFFECTS.

To some extent, greater than its effect upon the quasi-rigid earth, much less than its effect upon the fluid ocean, this varying tidal potential acts directly upon the molten magma body. Though this effect is real its amount undoubtedly is almost negligibly small. It is not observed.

SECONDARY TIDAL EFFECTS.

With the alternate increase and decrease in depth of the water in the ocean surrounding Hawaii which accompany the ebb and flow of the oceanic tides, it is conceivable that a variation is produced in the pressure on the bed of the ocean. This may compress and dilate alternately the subjacent molten body. However, in thinking of pressure variation from this cause, the fact must not be overlooked that this heaping of the ocean waters is a result *partly* of *lifting* potential. In any case at maximum this effect could vary from one time to another only by exceedingly small amounts, for the tide-wave is an almost infinitesimal element when considering the depth, and weight, of the ocean. A pressure variation due to this cause seems surely incompetent to produce the volcanic variations of longer period, *particularly the predominant variation of semi-annual period.*

Similarly the semi-diurnal earth deformations known as body-tides presumably compress and dilate the magma chamber, *in so far as they have time to act*, and these tides, like those in the ocean, undergo changes in the amount of their semi-diurnal effect with *fortnightly*, monthly, *semi-annual* and annual periods.

But unless their effect can be accumulated in some way, as Perret thinks, their force-changes of longer term are so small relatively that it does not seem probable that the observed volcanic variations can be due to them.

As to their accumulation, — it has been considered that the earth may not be sufficiently elastic to allow of completed action by the tide-force, before its reversal by rotation in the half-day, in the production of the semi-diurnal body-tide for example; but that ample time is afforded for equilibrium to be established in the case of tides of fortnightly period, or longer. If the earth is viscous, or of deficient rigidity, this matter of the time of action is of the highest importance.*

Recent work indicates a higher degree of elasticity than was postulated earlier.†

*Cf. The Physics of Earthquake Phenomena, C. G. Knott, pp. 102, 103, 105-106. (Professor Knott, having the occurrence of earthquakes in mind, also refers to the effects which might be expected from the action of the sun and moon in declination.)

†Cf. Michelson, A. A., Preliminary Results of Measurements of the Rigidity of the Earth, Jour. Geol. XXII, 2, Feb.-Mar., 1914.

However, accepting this *principle*, the tide-force of monthly period, which it is considered should be completely effective, is much greater than the tide-force of semi-annual period. But no volcanic response of monthly period is suggested by the observations, while a semi-annual fluctuation is the conspicuous thing. Incidentally there is no definite suggestion of any annual variation in eruption.

So, although with little doubt there is a certain amount of effect produced upon the volume of the magma reservoir, and thus upon the stand in Halemaumau, by all these tides of every period in the ocean and in the earth, and by the direct tides in the magma as well, — and although their effects may be accumulated in some degree as Perret suggests, — *this absence of a pronounced monthly variation in eruption*,
and the absence of a definite annual variation also, leads the writer to look further for explanation of the action at Kilauea.

SPECIAL EFFECTS DUE TO DECLINATION.

The luni-solar gravitational potential not only raises the tides and displaces the equatorial tide-crests to the north and south, but, in addition, because it acts at varying angles upon a *rotating, oblate spheroid* (as distinct from either a sphere or a quite irregular round form), it produces effects known in astronomy as the forced, semi-annual, solar nutation and the forced, semi-monthly, lunar nutation. These are very small forced deviations in the direction of the earth's axis of rotation. They are accomplished by the *inclined*, differential attraction exerted as a couple by the gravitational potential acting at the varying angle of declination of the attracting body upon the earth's equatorial protuberance, — or more exactly, upon the earth's spheroidal figure, since every earth particle is concerned in the integration by which the effect is brought about. The sum of these effects with others gives rise to the progressive change in the direction of the earth's axis of rotation known as the precession of the equinoxes.

While this action and its mechanism are well known to astronomical readers, nevertheless it seems advantageous for this study to explain it at a little length. It will suffice to deal only with the sun's action, neglecting temporarily that of the moon.

At times of equinox

> the lines in the field of force of the sun's attraction for the earth (more strictly, of the mutual sun-earth attraction),
>
> lie in, or parallel with, the plane of the earth's equator, which also is the plane of the so-called *protuberance* of earth matter, a property of the spheroidal earth arising from its rotation.

As the sun leaves the equinoctial position and progresses in its apparent motion towards and to its position at the time of solstice, the direction of mutual sun-earth attraction swings out of parallelism with the plane of the earth's equator until,

at times of solstice
these lines in the sun-earth force-field
stand at an angle of 23½ degrees, approximately
with the equatorial plane of the spheroidal earth.
Consequently,
at all times, except at the epoch of equinox,
with the maximum effect attained
at solstice (and on account of *lag*, for an indefinite interval thereafter),
the sun exerts attraction
not only upon the earth as a whole, but in part also distinctively upon the protuberance (or rather upon the spheroidal figure as such),
whose plane is no longer parallel with the field of force.
Therefore, owing to differences in the distances of the earth particles from the sun
(but disregarding, in this connection, the diurnal effect of tidal distortion in the earth's body)
an effect of this field of force
is to exert upon the equatorial protuberance
a couple which tends to swing it into the plane of the ecliptic.

But this tendency is very powerfully resisted by the earth's great gyrostatic action due to its great mass and rapid rotation.
This action tends to maintain without change
the directions
of the equatorial plane of the spheroid, and
of its axis of rotation.
The gyrostatic tendency is far greater than the tilting tendency and is of continual duration and practically constant amount. Consequently, the nutations resulting from the varying tilting couple are very small.

Meantime the so-called centrifugal action tends to maintain without significant change the oblate spheroidal form of the earth as referred to the axis of rotation.

Further, it is clear that the force component responsible for the tilting tendency, due to change of direction of the field of force relative to the plane of the earth's equator, is not steady but varies from zero at equinox through a maximum at solstice to zero again at equinox.

Hence the deviations in direction of the earth's axis of rotation do not take place in a smooth, fluent way but are effected by a series of *tugs*, or prolonged varying impulses, and these produce the progressive changes in the direction of the earth's axis of rotation by a series of impelled "noddings."
This action is the
forced, semi-annual, solar nutation.

There also is an identically similar
forced, semi-monthly, lunar nutation
due to the action of the moon in declination.

> There are further factors in the precessional motion due to action of the planets, but these are so minute in amount that they are negligible in such a study as this. Another nutation, due to the changing angle of the orbit of the moon, is implicitly taken into account in the numerical approximations undertaken beyond.

These nutations are produced by the integration of this effect of inclined attraction upon each and every particle in the earth. If the earth were strictly rigid in the mathematical sense this action would produce only nutation and precession. But the earth is only quasi-rigid and, therefore, in addition to the tilting tendency, a tendency to the reconstitution, or readjustment, of the internal configuration of the earth particles may be expected. Therefore, in this study it is considered that *strains* or *deformations* are produced which wax and wane with these nutations; and that, as a first approximation, these may be taken as proportional in amount to that of the nutations they accompany. Therefore, these strains must be very small in amount.

The critical attention of qualified readers is directed to this conception, its development here, and the crude, quantitative approximation made below. For this is the crucial idea in the hypothetical part of this work.

Consequently we must now examine the relative amounts of these forced nutations. This also is a matter familiar to astronomical readers, but it is deemed of advantage to set it forth clearly here.

Now, while
the gravitational attraction of one body for another varies
directly as the masses, and
inversely as the *square* of the distance between them
the precession-producing capacity of a body, such as sun, or moon
(that component of the attraction exerted as a couple upon the spheroidal form, as such, so as to produce forced nutation, and precession),
varies
inversely as the *cube* of the distance of the disturbing body. Whence this precession-producing force may be greater for a small body near at hand, like the moon, than for a great body at great distance, like the sun. So it happens that while the effectiveness of the sun's direct attraction upon the earth is about 175 times as great as the moon's direct attraction, the precession-producing capacity of the moon is more than twice as great as that of the sun.

But, *and this is a point of prime importance*,
the moon-force varies from zero through its maximum to zero again in half the lunar month, while
the sun-force varies similarly through a period of half the solar, or ordinary, year.
Now, in consequence of this large difference in the *time interval* through which these forces respectively act,
the forced, semi-annual, solar nutation,

produced by the weaker sun-force,
is about 1.2 seconds of arc,
(this is the amount of deviation produced in the direction of the earth's axis of rotation),
while the corresponding
forced, semi-monthly, lunar nutation,
produced by the stronger moon-force,
does not exceed 0.1 of a second of arc.

Further,
there is an
18.6 yearly variation
in the value
of the
forced,
semi-monthly, lunar
nutation
due to
the
Regression
of the
Nodes.

When the ascending node of the moon's orbit is near the autumnal equinox, the inclination of the orbit to the earth's equator is only about 18 degrees, while about nine and a third years later, when the ascending node has backed around the ecliptic to the neighborhood of the vernal equinox, the inclination of the orbit to the equator is about 28 degrees. Hence at this latter time the moon will produce nearly twice as *precessional* movement each month as at the former time. Hence the forced, semi-monthly nutation must increase and decrease in a proportional way, and along with it the associated earth strain here hypothesized.

For convenience of expression the earth strains under consideration may be referred to as nutational strains. Without attempting to determine their resultant directly they will be treated as force-effects of distinct periods, the smaller superimposed upon the greater.

Since, at its greatest, the amount of the forced, lunar nutation is less than 8% of the amount of the forced, solar nutation, although the moon-force is the greater, the resulting earth strains are here supposed to be related in approximately the same degree. Such a relation appears to accord closely with the supposed responses in Halemaumau.

Obviously a thorough treatment of this force, and strain, variation would require an elaborate mathematical analysis for which the numerical coefficients should be determined by adequate *measurements* of all the factors involved. Also such an analysis should take account of force, and strain, factors due to tides in the magma, the tides in the ocean, and the earth tides, of all periods; and it should involve consideration of solar and lunar distances, and of the phases of the moon.

So complete an analysis would be extraordinarily difficult. It is out of the question here. However, even for *qualitative* purposes, some sort of numerical treatment is required for the testing of the hypothesis. The following crude approximation has been attempted.

COMPUTATION OF APPROXIMATE NUMERICAL EQUIVALENTS.

SOLAR EQUIVALENTS.

For the present study it has seemed legitimate and useful to take as numerical equivalents for the solar, nutational earth-strain
simply
the numerical values
of the concomitant angles of solar declination,
(expressing degrees as units and parts of degrees as decimals).

> Of course the forces of the precessional couple vary as some function involving the sine of the declination angle; so — strictly, it would be better procedure to take the natural sines of the concomitant angles as numerical equivalents for the value of strain. However, since none of the angles in question (including those encountered in lunar declination also) exceed 30 degrees, the *form* of the curve indicating earth strain thus obtained would not differ (but only its numerical ordinate values), from that based upon the direct angular values. Neither set of numbers would have any quantitative value of an absolute nature. The angle numbers are more convenient to obtain than their sines, and so are used.

To these slowly-varying, numerical equivalents for the solar, nutational earth strain are added, arithmetically in all cases, numerical equivalents for the lesser and more rapidly-varying, lunar, nutational strain.

LUNAR EQUIVALENTS.

Now, *in mechanism*, the action of the moon is identical with that of the sun. Nevertheless,
at maximum
the measured value of the forced, semi-monthly, lunar nutation
is less than 8% of
the measured value of the forced, semi-annual, solar nutation.
Moreover,
at maximum
the declination of the moon is somewhat greater (over 28 degrees)
than that reached by the sun at its maximum (less than 24 degrees)
Consequently,
if we are to consider the strain in the earth produced by the moon as directly proportional to the forced, lunar nutation, and some function of the declination of the moon, *which undergoes substantial periodic variation through the cycle of 18.6 years*,
we must take for
numerical equivalents for the strain generated by the moon
not the numerical values of the lunar declination angles
(as we did for the case of the solar equivalents),
but numbers which are less than 8% of these.

Once again it seems practically necessary to discuss the matter in greater detail than astronomical students would require. Unavoidably this involves some repetition.

In consequence of the moon's orbital motion there occur very slight changes, from one fortnight to the next, in the amounts of the fortnightly maximum angles of declination, which go on through the cycle of 18.6 years. Thus comes about a gradual change in the amount of the successive impulses of the moon's precessional force, and so in the resulting nutation and strain. This considerably complicates the procedure for approximating the lunar, numerical equivalents.

At its greatest when the lunar declination at each fortnightly maximum is
    in excess of 28 degrees
the measured value of the forced. lunar nutation, and so of the earth strain, is less than 8% of
the measured value of the forced, solar nutation, or strain.
    While
at its least, about nine and a third years later,
    when the lunar declination at each fortnightly maximum
    is only about 18 degrees,
the forced lunar nutation, and strain,
must be much less
    both absolutely
    and in relation to the solar effect.
Thus we conceive that there will occur
a maximum group
    of fortnightly maxima of earth strain
        when the declination of the moon's orbit is about 28 degrees,
    and
a minimum group
    of such maxima of earth strain
        when the orbit is inclined only about 18 degrees.

And these maxima of earth strain will vary, as their causes do, by very slight changes from one fortnight to the next through the cycle of 18.6 years.

Therefore we must try to approximate
what varying percentages
    of the numerical values of the lunar declination angles
may be employed, from fortnight to fortnight,
to indicate the amount of the lunar nutational strain.
This moon force, and effect, probably varies as some function involving the sine of the fortnightly maximum of declination.

For present purposes, *suppose* these effects to vary directly as these sines. Further to facilitate the computation, let us *assume* that the value of lunar nutational earth strain
    when the fortnightly maximum angle of declination is *exactly* 28 degrees
may be taken as 7.5% of
    this numerical value of lunar declination.

On these assumptions we then obtain as
numerical equivalents for lunar nutational earth strain
numbers
which are 7.5%
  of the numerical values of the lunar declination angles from epoch to epoch when the fortnightly maximum is 28 degrees, and
which are x%
  of the numerical values of these angles when the fortnightly maximum is greater or less than 28 degrees,
where x varies directly as the sines of the corresponding fortnightly maxima. x is found by proportioning with the slide-rule, setting 7.5% over 0.4695, the nat sin of 28 degrees, as gage point.

By adding arithmetically the numerical lunar equivalents thus obtained to the numerical solar equivalents for corresponding successive days a crude strain almanac is computed.
A portion of this almanac for this study appears as an appendix.

THE STRAIN CURVE.

The resulting numbers are used to construct a time curve of strain which exhibits semi-annual arches of relatively large amplitude built up of semi-monthly arches, of smaller magnitude, touching end to end. This curve is considered to express **crudely** the relative amounts of the forced nutational strains; and to indicate approximately the times of occurrence of the major and minor strain crises, but in this latter respect it is defective in that it does not exhibit *the real effect of lag.* The amount of this is unknown. It awaits empirical data and reduction.

With regard to the fortnightly branches it is recognized further that theoretically there should be, and practically there is, observed a greater response of the volcano when the conditions of syzygy or perigee, or both, occur at times near the fortnightly maxima of the curve; and that conversely volcanic responses should be, and are, less pronounced when quadrature or apogee, or both, occur near these fortnightly crests. For such reason the times of occurrence of these factors are indicated on the curve diagram; but, since the amounts of these additional effects, though seemingly slight, are quite indeterminate, they have not been taken into account numerically, in computing the curve points.

So, to recapitulate, — the writer tentatively considers these nutational strains to be the predominating factors in producing the short term cyclical changes at Kilauea. It is thought that the action here hypothesized causes a very minute strain of the spheroid as a whole which grows from a value we may regard as null at equinox to a maximum value lagging after solstice, with a similar, small, fortnightly change. It is conceived that this strain produces *very minute* alternating volume changes in the occluded magma reservoir, bringing magnified responses at the top of the surface conduits as already explained. And the degree of compression of the magma body is believed to grow positively from equinox until after solstice, whether the sun wanders north or south, being caused chiefly by growing earth strain and not due, except possibly in very subordinate degree, to change in location of tide crest maxima.

Great emphasis is placed upon the effect of the *factor of time* both in regard to the building of the strain and to the production of lag.

SOME CRITICAL CONSIDERATIONS.

At this point it is desirable to point out that *precise* responses by the magma to the strain crises indicated by this curve should not be looked for. This does not imply want of confidence in the hypothesis. But certain factors have been neglected. The tide effects already mentioned are not indicated by the curve. Also there are secular, and sporadic, effects of terrestrial origin, — such as strains produced by isostatic movements, widespread changes in physical-chemical conditions, etc. Even if we exclude these, we must take account of the facts that

(*a*) the magma is not a simple fluid but is a viscous aggregate almost undoubtedly made up of both gas and fluid phases discretely intermingled, with dissolved gases also, and probably with minute crystalline phases; while, through circulation, portions are undergoing comparatively rapid pressure changes with accompanying chemical interaction and the absorption or liberation of heat with changes in gas tension, — in short, that the magma column is a viscous column, with a convectional circulation and a mechanism of frothing at its top, — whence its responses to the nutational strain variation both in height of stand, and
in vigor of surface action,
would be confused with other responses to its own turbulent, internal condition; and that

(*b*) the sizes, and shapes, of cross-sections of the magma conduit are continually undergoing changes of appreciable magnitude. This latter, of course, may hold true only very near the surface.

Also it will be easy to realize that, though of undoubted reality, variations in the nature, intensity and gross energy of surface action are difficult to characterize or describe effectively — or to estimate or discriminate in any quantitative way, for we have as yet no means of measuring or standardizing the numerous factors which combine to produce the surface changes. Therefore, correlations of action of this kind with the strain curve are necessarily subjective and thus liable to prejudice in some degree. Even if free of error they are difficult to establish, and to indicate graphically. This is an unavoidable condition. All that can be done is to exercise care and judgment in applying this test, and it must be made on the ground from day to day.

Hence the similitude of rising and falling action in Halemaumau with that of mercury in a barometer tube is necessarily very imperfect, and a general tendency to respond is all that can be expected. Such a tendency, it is believed, is noted.

To illustrate, — at stages of action in Kilauea most favorable to this hypothesis there are observed definite rising and increase in vigor of surface action at, and (or), immediately after times of maxima indicated by the strain curve here constructed, — succeeded by definite falling with decrease of action at times of indicated minima. However, it has often been the case that a general increase (or decrease) has been going on, presumably in response to some set of causes not considered here; at such stages, times when the curve indicates decreasing strain have commonly been marked by pauses in the rising, or increasing of activity, — or at any rate, by much slower increase in action. Analogous contrary statements hold true for times when a general decrease seems to be going on.

Rarely circumstances have been noted which do not tally with this curve of earth strain, and that cannot be explained on the basis indicated above. These are genuine anomalies not yet understood.

There have been times of comparatively rapid drainage in Halemaumau which could reasonably be associated with seismic crises. Only in a secondary sense should these be correlated with this curve, for though the magma falls it is conceivably as a result of *excessive* strain, producing rupture and thus providing a drainage channel. These cases are too few to interfere with the correlation as a whole.

IV. FURTHER HYPOTHETICAL CONSIDERATIONS.

The Chandler Nutation in Relation to Earth Strain.

There is, probably, a further, important, confusing factor arising from responses by the magma system to earth distortion of longer period produced by the "free nutation" of the earth discovered by Chandler. This can be treated here only in a general way, for the *sense* of this response has not been worked out thoroughly as yet. The writer has been unable to obtain access to the complete data of measurement of latitude variation. Also he has been unable to see certain important theoretical papers. The mechanism of action is clear but the direction of the response is not. Consequently not much emphasis can be placed as yet upon this part of the hypothetical development.

It is convenient to introduce this matter by quoting from Darwin's lectures on the "Tides."*

> "The equator must now be defined as a plane through the earth's centre at right angles to the axis of rotation, and not as a plane fixed with reference to the solid earth. The latitude of any place is the angle† between the equator and a line drawn from the centre of the earth to the place of observation. Now when the earth nutates (freely), the axis of rotation shifts, and its extremity describes a small circle round the spot which is usually described as the pole‡. The equator, being perpendicular to the axis of rotation, of course shifts also, and therefore the latitude of a place fixed on the solid earth varies. During the whole course of the nutation, the earth's axis of rotation is always directed toward the same point in the heavens§, and therefore the angle between the celestial pole and the vertical or plumb-line at the place of observation must oscillate about some mean value; the period of the oscillation is that of the earth's nutation. This movement is called a 'free' nutation, because it is independent of the action of external forces.
>
> "† This angle is technically called the geocentric latitude; the distinction between true and geocentric latitude is immaterial in the present discussion."

The above paragraph from Darwin is very condensed; for ease and accuracy of comprehension, for workers in geology, at any rate, it requires explanation and expansion.

Before proceeding further we must take note that as Darwin has defined it here *the equator is a physical plane*, — a plane made up of physical par-

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*The Tides, pp. 251-252, et seq.
G. H. Darwin, Boston, 1898.

‡ It would be more precise to say:—The north and south poles, instead of being fixed points on the earth's surface, wander around within a circle about 50 feet in diameter.

§ As we know from the discussion earlier in this study, — this statement as to the fixity of direction of the rotation axis needs to be modified. In a later paragraph Darwin modifies it. Also, it is restated in the discussion below.

ticles, comprising all in that plane through the centre perpendicular to *the earth's axis of rotation* which is a *physical diameter*, a rectilinear series of physical particles such that the end particles, at the poles, always lie within the circle of wandering above mentioned.

When, without action of external forces, this free nutation takes place, the earth spins irregularly like a top out of balance. But, as Darwin points out, *this* motion does not produce change in the *direction* of the earth's axis of rotation.

Owing, however, to the *external* precessional forces, as we have seen above, the direction of the axis of rotation *does* undergo a cyclically progressive change — but this goes on outside the frame of reference in which the present, "free" motion takes place.

In the course of the free nutation the shifting of the axis of rotation brings one physical, circumpolar diameter after another into coincidence with the (locally) "fixed" direction of the rotation axis. Hence, one after another, these serve, for the time being, as the axis of rotation — and, consequently, *as the axis of centrifugal repulsion;* and the physical planes at right angles to these diameters are, each in turn, for like intervals, the plane of the equator, — *and of the equatorial protuberance.*

Failure to distinguish clearly between the causes, action and effects of the "free" and the "forced" nutations is sure to lead to confused understanding.

The free nutation consists of a kind of wabbling motion in the spinning of the earth, due to mechanical causes apart from the direct action of any external forces, — as a result of which the earth's mean axis of figure sweeps out an irregular cone-like surface round the "fixed" direction of the rotation axis. It involves very minute changes in the configuration of the earth.

The forced nutations, due to the differential action of the external forces of attraction of the sun and moon upon the equatorial protuberance, produce minute, cyclical changes (which when summed constitute the slow, progressive, precessional motion) of the direction of the "fixed" axis to which the free nutational motion is referred. Also, as already pointed out, these forced nutations are considered to produce very minute changes in the configuration of the earth.

An admirably clear exposition of the cause of free nutation, its magnitude, mechanism and periods, is given in an article written by the late Simon Newcomb in the Encyclopedia Britannica.*

From this article we may select and emphasize the chief conclusions as follows: — a periodic variation of latitude is found by observation; changes in earth configuration, proportional in amount, accompany it, — involving incessant reconstitution of the equatorial protuberance; the resultant period of the variation is very nearly 14 months; the gross amount of the variation undergoes change, owing to the combination of the effects of meteorological and similar disturbances with the Eulerian motion proper, so that if, at a given time, the range in 14 months is small, then 3 to 4 years later it will be large, — this change having a 7-years period, nearly.

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*Encyclo. Britann., Eleventh Ed., XVI, 267-68.

At all times the variation in latitude is rather small. Its average value for the 14-months period is seen to be about 0.30″ (2 x 0.15″), or about 30 feet. The extreme shift so far observed is somewhat more than 0.60″, or about 60 feet. During the years 1893-1900 an extensive study of this variation of latitude, conducted at Columbia University, developed that the latitude there was lowest on September 15, 1895, and highest on August 22, 1897. Between these extremes the variation amounted to 0.696″, or nearly 70 feet.*

The actual motion of the instantaneous pole around the mean pole within the circumpolar tract is highly complicated, as its diagrammatic representation shows. Owing to meteorological irregularities the path of the annual component, a narrow ellipse about 30 feet long, undergoes irregular changes of form and position, thus introducing irregularity into the resultant path. Other changes, such as denudation and deposition, volcanic eruption, earth-shifts accompanying great earthquakes, etc., contribute to the irregularities.

This periodic, though irregular, variation in latitude, causing a periodic, irregular, incessant change in the configuration of the earth, must entail an irregular waxing and waning in the state of elastic strain in the earth throughout the period of 14 months. Unless of negligible magnitude, this strain variation must find responses in the conditions of activity of such a volcano as Kilauea.

Also, since the gross value of the latitude variation, and so of the strain variation, undergoes marked change in a period of 7 years, we must look for a similar change in the volcanic responses. The amount of this and its period may be somewhat irregular, both on account of irregularity in the factor of causation, and on account of local confusing action.

Although the sense of the response to this strain is not thoroughly understood, it may be worth while to review the quantities involved. Tentatively, at maximum, the change in latitude at any place in any single period of 14 months may amount to a little more than 0.6″; and epochs may be chosen in such a period so that all, or nearly all, the change at the selected station will occur between dates about 7 months apart. This means that in a 7-months period the physical axis of rotation has shifted through an angle of 0.6″ from one circumpolar diameter to another on the opposite side, geographically, of the mean axis of figure.

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*Nautical Science, pp. 36-37.
C. L. Poor, New York, 1910.

Hence from one extreme epoch to the other, 7 months later, strain throughout a given region, such as the Hawaiian group, has been undergoing progressive change in a given direction, *whether increasing or decreasing.* Thus this strain grows continuously through an interval 2⅓ times as great as that from equinox to solstice. However, it seems probable that the factor of *lag* is here less important than in the case of forced nutational strain; for external forces are not directly concerned in the causation, so that the changing figure may well be near to its equilibrium configuration at all times. As latitude varies irregularly there would be terms of more rapid and of slower strain building, but this need not be discussed in detail until the sense of the action is understood.

In other respects it is difficult to compare these strain causes. For one is due to the inclined, differential attraction of the sun upon the yielding spheroidal figure in incessant conflict with the gyrostatic tendency which produces a change in the *celestial* direction of the rotation axis amounting to 1.2″ of arc, — while the other is due to the shifting of one physical diameter after another into the position of the axis of centrifugal repulsion, so that geographically opposed rotation diameters may be inclined to each other by as much as 0.6″ of arc. Consequently no attempt can be made here to compare these strains as to quantity *genetically*, — but in the study of the volcanic record the suggestion arises that the 7-year variation in the gross amount of the "free" nutational strain is a conspicuous factor, and very likely much greater than the semi-annual variation due to "forced" nutation.

If this is so, at a time of maximum range the growth of this strain during a 7-months period may be greater than the corresponding growth in "forced" strain in the equinox-solstice interval. And the maximum of "free" strain might occur in such a time relation to the maximum of "forced" strain as to offset completely, or to overwhelm, the solar effect in a certain half-year. In that case during the preceding and following half-years these factors should nearly coincide, — in other words, *in a given region*, under certain circumstances as to time of maximum, a 14-months variation in volcanic response might be looked for, rather than the usual 6-months period, or one of 7 months. This would be most conspicuous if a maximum of "free" strain should fall at or near solstice; least so if it should fall at or near equinox. Of course this effect should be most conspicuous at times of great latitude departure.

In more general terms, — at a given locality any volcanic effects due to strain arising from variation of latitude should exhibit periods of about 14 months between like phases, such as southing to southing, or northing to northing. Thus strain maxima from this cause may sometimes coincide with soli-lunar maxima, sometimes with soli-lunar minima, but most often with intervening phases of the soli-lunar strain variation. Consequently there may occur a great many combinations of *phase* and *amount* of the effects due to strain from these causes. Therefore, disregarding for the moment all other factors in volcanic action, the response of volcanoes to such variation in strain should be positive but, from these causes alone, highly complicated.

Further it is especially to be noted that northing, or southing, of the region of some particular meridian will occur, in some particular year, at solstice along with the maximum of soli-lunar strain. Whence at solstices immediately preceding or following the northing, or southing, will occur in regions along some other meridian. There is thus introduced a geographical positioning of the regions of greatest expectable strain at time of solstice, — a meridional shifting with a period of about, but not exactly, 7 years.

To follow this a little further still, — since the amount of the soli-lunar stress undergoes slight changes from year to year, owing to the variation in the lunar factor due to the regression of the nodes, and the amount of the latitude strain undergoes large changes in a period of about 7 years, further complications are introduced which will tend to bring epochs of major maxima of strain at longer, and possibly somewhat irregular, intervals, — irregular owing to the changing character of the annual term in latitude variation. And these maxima should also exhibit positioning in geographic longitude.

With this in mind it is interesting to note, — but without placing any emphasis on the correspondences brought out, — that Omori* has shown that, in the case of eruptions of Asama-yama, considered in groups, there has been an average interval of 63½ years, with a double interval, which he emphasizes. of 126 years.

In connection with this the following train of reasoning is interesting.

With reference to a particular quadrant of meridian, and its opposite quadrant (probably with supplementary effects in both the adjacent quadrants of meridian), it will sometimes happen that at a solstice configuration which occurs at a time when, in the cycle of the regression of the nodes, the fortnightly maxima of declination are reaching their greatest values, there will also occur the greatest extreme of latitude shift, favorable to strain building on the given meridian, in the course of the 7-year variation in magnitude. At such an epoch the earth strains here hypothesized

(*a*). from the combined "forced" nutations, and

(*b*) from the "free" nutation

will simultaneously attain their maximum and a

grand maximum of earth strain, and its attendant responses, should result.

Now the least common multiple of these periods, of about 7 years, and of about 18.6 years, is *about 130 years*. And the half-interval is *about 65 years*.

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*The Eruptions and Earthquakes of the Asama-yama, Bull. I. E. I. C., VI, 1, pp. 20-21. F. Omori.

Hence at a given longitude these grand maxima should be expected at intervals of about 130 years with, possibly, supplementary maxima at intervals of about 65 years.

This is sufficiently near to Omori's* reduced interval to be suggestive.

Also it will do no harm to note that in 1789, or 1790, there was a grand explosive outburst at Kilauea. And that in 1855, 65 or 66 years later, there was a period of activity in the sink crater considered by some the greatest subsequent action here, at least apart from seismic crises. But such a correlation rests upon few observations, and depends, on the theoretical side, upon a highly complicated train of circumstances.

Moreover, there is no reason for thinking these grand maxima of strain to be *greatly* in excess of the minor maxima of nearly contemporaneous occurrence. So this correlation, and this portion of the hypothesis, do not at present deserve emphasis, — merely notice.

In the present state of knowledge it is unprofitable to follow hypothetical considerations further. And, indeed, in this study most emphasis rests upon the recognition and explanation of the fortnightly and semi-annual periods.

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*In a later article Omori further states: — "... Thus the double-length of 63½ x 2 equals 127, or, say, 130 years, may also be regarded as a possible period in the frequency variation of the eruptions; and it is noteworthy that the Asama-yama, the O-shima, and the Sakura-jima, which made no great outbursts since the Anei-Temmei times, have exhibited, just after the lapse of 130 years, again extraordinary activity within the recent years."
F. Omori, Bull. I. E. I. C., VIII, 1, p. 6.

V. THE DATA OF OBSERVATION OF THE VOLCANO.

It is not the purpose of the writer to argue in support of the hypothesis which has been developed in so great detail. He merely presents for correlation, practically without comment, the data of the volcanic record at Kilauea. In this his judgment does not enter, nor prejudice, except to a very slight degree in the selection among multitudinous statements of observation in the later years, and thus in possible, unconscious emphasis given to these. It should be needless to say that he has guarded so far as possible against bias in the matter.

For presentation the volcanic evidence is divided into three groups:

(A) the sparse and irregularly distributed observations earlier than 1865, stated in a systematic, chronological way;

(B) the much more frequent, but still scant and irregular, observations recorded between 1865 and the summer of 1911, which afford some detailed and explicit evidence, — assembled on charts to exhibit the changes from month to month through the years, in such a way as to afford a rough test by inspection of the semi-annual variation especially, and less definitely of the variation during terms of 14 months, or longer;

(C) the measurements and routine observations since June, 1911, correlated on charts with the hypothetical strain curve computed here. These observations are the work of Perret, to whom the writer is indebted for a copy of the curve of the stand of magma during July-September, 1911, which is re-drawn here; and of the staff of the Hawaiian Volcano Observatory. For the assemblage of the latter data the writer is indebted in considerable measure to Professor T. A. Jaggar, Jr., the Director of the Observatory.

(A) The Data from 1823 to 1865.

1823, August, Visited by the Rev. William Ellis.
Inferred recent sinking of molten lava in Kilauea
(March) owing to outbreak and flow at south in March.
Depth, from summit surface to molten lava estimated at 800 feet. (Probably bad estimate, see 1825.)
Activity, great.

1824, 16 June, Visited by E. Loomis.
Depth, below surface at S. end of crater estimated at 800-900 feet. Apparently lower than the year before. There was an additional, lower, "black ledge," and an inner pit.
Activity, less than the year before.

1825. 28 July, (June?) Visited by a party which included
Lord Byron (George Anson),
Rev. C. S. Stewart,
Lieut. Malden (who made a sketch-survey) and
R. Dampier (who made sketches of the scene).
Depth, still greater than in 1824,
"calculated" by Malden at
1500 feet below summit surface at the west.*
Activity, greater than in 1824.

December, Visited by the Rev. A. Bishop.
Depth, less (!!!) than in 1823, lava 400 feet higher.
Activity, very great.

1826, Letter from Maui, of the latter part of the year:
Depth, Activity, "It is now reported here, that the volcano on Hawaii is in very vigorous action, and that the boiling lava has risen several hundred feet in the crater."

1827, Editorial note to printed extracts from Mr. Bishop's Journal, publ. in Miss. Herald:
Depth, "The crater . . . has been found by actual measurement to be . . . in its ordinary state. one thousand feet in depth."
(Referring to Malden's measurement, ? Ed.)

1829, October, (early in) Visited by the Rev. C. S. Stewart (again).
Depth, to molten lava less by about 200 feet than in 1825 in July; hence total depth about
1300 feet.
Activity, great.

1830, 20-21 October, Visited by the Rev. Hiram Bingham.
Depths, estimated,
600 feet to the "black ledge,"
1000 feet to the molten lava surface.
Activity, very considerable.

1831, July, Visited by the Rev. Joseph Goodrich.
Depth, less by about 900 feet than in 1823,
50 feet higher than the "black ledge."
Activity, condition not described.

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* Cf. comment by Dana in "Characteristics of Volcanoes," pp. 50-51.

1832,	7 May,	Letter of Messrs. Green and Dibble, publ. in Miss. Herald, 1833, p. 57.
	9-10 January	Earthquakes, outbreak and flow from Byron's
	Depth,	Ledge, draining (?) inner part of crater.
	Activity,	very great, brilliant glow seen (from Hilo?) on the evening of January 9, succeeded by sluggish conditions after the eruption.
	November,	Visited by the Rev. Joseph Goodrich.
	Depth,	"as at first," that is, about 900 feet below the "black ledge," or 1750 feet below the summit surface (according to Hitchcock's interpretation) or 400 feet, about, below the "black ledge" (according to Brigham's interpretation).
	Activity,	somewhat lessened when seen in November.
1833	12 January,	Visited by the Rev. W. P. Alexander.
	Depth,	estimated at 2000 feet; no mention of the "black ledge."
	Activity,	ordinary for that time.
1834,		Visited by David Douglas.
	Depth,	to lava surface, measured barometrically, about 1120 feet.
	Activity,	slightly greater than in 1833.
1835,		Visited by Charles Burnham.
	Depth,	estimated at 800 feet.
	Activity,	not definitely described.
1837,	August,	Visited by S. N. Castle.
	Depth,	of molten lava only slightly greater than that of the "black ledge."
	Activity,	ordinary.
1838,	8 May,	Visited by Capt. Chase and Capt. Parker.
	Depth,	of molten lava slightly greater than that of the "black ledge."
	Activity,	considerable.
	Aug. or Sept.,	Visited by Count Strzelecki.
	Depth,	to floor ("black ledge") at northeast, by barometer 600 feet. Molten lava perhaps at higher level, confined by spatter ramparts.
	Activity,	considerable.

1839, 16 September, Visited by Capt. John Shepherd, R. N.
Depth, not so great as former level of the "black ledge," now obliterated. About Halemaumau a cone rose about 100 feet above the floor of the crater and from this lava overflowed at times.
Activity, not otherwise described.

From 1840 until 1865 all information quoted here is derived from letters and statements of the Rev. Titus Coan, of Hilo, Hawaii, except as otherwise noted.

1840, 25 September (Date of letter.)
(May-June),
Depth, to the "black ledge," and so to the average level of the molten lava, had been decreased by more than 50 feet, owing to frequent overflowing.
Activity, terrific, throughout the latter part of May, then
Eruption, beginning May 30, with a flow in Puna, continuing for three weeks, and
(Depth) draining the crater.

November, Visited by J. D. Dana, and other members of the Wilkes Expedition.
Depth, below a "black ledge" higher than that earlier referred to, because up-built by overflow, but rejuvenated by the collapse,
340 feet; total depth about 1000 feet.
Activity, relatively slight.

17 December, Wilkes' Narrative; U. S. Exploring Expedition.
Depth, afterward found to be
"660 feet" from the north rim to the "black ledge,"
"384 feet" from "black ledge" to floor of crater,
"987 feet" (?) in total.
Activity, apparently ordinary.

1841, 16 January, Wilkes' Narrative (Dr. Judd).
Depth, chief lake 20 feet below rim of steeply sloping spatter rampart;
sudden break-up and filling, in ten to fifteen minutes, of small pit (Judd's Lake), about 38 feet deep by about 200 feet in diameter.
Activity, apparently considerable.

16-17 January, Wilkes.
Depth, Surface of chief lake fell rapidly during night, Judd's Lake continued overflowing.
Activity, less.

17 January, Wilkes.
Depth, "650 feet" from "black ledge" to north rim; "342 feet" from "black ledge" to the bottom, a 100-foot fall during the night, for
"120 feet" from spatter rim to surface of lake;
"992 feet" from the north rim to the bottom.
Activity, sluggish.

22 January, Wilkes' Narrative (Dr. Pickering).
Depth, 30 feet from spatter rim to the surface of the lake.
Activity, only ordinary.

1842, February,
Depth, not clearly stated, but nearly 100 feet less than on previous visit; probably greater, as yet, than that of the rejuvenated black ledge.
Activity, ordinary for that time.

1844, July,
Depth, not clearly stated; but overflowing from Halemaumau on all sides of its spatter embankments.
Activity, apparently considerable.

1846, June, (Letter of June 25).
Depth, in places less than that of the "black ledge."
Activity, "great lake is intensely active most of the time."

July, Visited by C. S. Lyman.
Depth, less by 400-500 feet than in 1830, in places less than that of the "black ledge."
Activity, moderate for that time.

7 December,
Depth, less than in June.
Activity, very considerable.

1847, July, (Letter of January, 1851).
Depth, indeterminate, lake overflowing and thus building up the region immediately around it, but at this time not the more remote parts of the crater.
Activity, not described.

1848, (Letter of January, 1851.)
Depth, indeterminate, but greatly reduced. Thick crust formed over Halemaumau, and then *elevated* into a dome early in this year, rising until in August almost high enough to overtop the lower part of the outer wall of Kilauea and look out upon the surrounding country.
Activity, of usual kinds very slight; sluggish flows from fissures in the sides of the dome. During a great part of the summer and autumn there was no "fire" visible, even at night.

1849, April-May, (Letter of January, 1851.)
Depth, indeterminate; dome over Halemaumau.
Activity, violent, — of a minor explosive kind.
Flows from fissures in the sides of the dome.
". . . nearly the whole bottom of Kilauea was quivering and cracking with heat," succeeded by greatly lessened activity,
(Depth) with inferred subterranean drainage.

1850, December, (Letter of January, 1851.)
Depth, indeterminate; presumably little changed.
Activity, "steaming stupefaction."
"During December, 1850, the smoke and steam are said to have much increased; and the occasional throe of an earthquake indicates that all subterranean action has not ceased."

1851, Depth, presumably little changed; dome over Halemaumau.
Activity, "There is now one cone feebly active at a little distance from the dome in the crater."
"steaming stupefaction."

1852, March-July, (Letter of July, 1852.)
Depth, presumably little changed; dome over Halemaumau, but with its keystone region collapsed.
Activity, in March very considerable;
in July much increased.

1853, "latter part of year"
(Letter of January 30, 1854.)
Depth, of central lava platform less by 600 feet than after the eruption in 1840. In some places less by 200 feet than the outer portion of the "black ledge."
Activity, a lake within the partially collapsed dome.

1854,		
	Depth,	not mentioned; presumably little or no change.
	Activity,	unusually dull throughout the year.
1855,		(Letter of July 18, 1855.)
	May-June,	for a fortnight, according to reports by visitors,
	Depth,	not indicated clearly, but
	Activity,	extreme and terrifying
		(Accepting these accounts this constitutes the most active period on record at Kilauea.)
	6 July,	(Letter of July 18, 1855.)
	Depth,	of molten lava below the rim of Halemaumau, perhaps 75 feet.
	Activity,	though still very great was lessened, but there was much Pele's Hair all about.
	8 September,	(Editorial in "The Friend," by S. C. Damon).
	Activity,	still very great.
		(Letter of October 22, 1855.)
	Depth,	at inner periphery of "black ledge" less by about 200 feet than in April; but below rim of *collapsed dome* of Halemaumau, about 100 feet.
	14 November,	Visited by F. G. Weld, and Stuart Wortley.
	Depth,	(quotation by Hitchcock seems ambiguous.)
	Activity,	much decreased, only glow holes, no lake of "fire."
1856,	(March),	(Letter of October 22, 1856.)
	Depth,	of central floor of the crater remained without change, 600 feet less than in 1840.
	Activity,	sluggish in Halemaumau; "thousands of steam vents" (according to J. H. Wood).
	Depth,	of molten lava 20 feet greater than the adjacent floor of the crater, but enclosed by a spatter rampart about 30 feet high.
	Activity,	only ordinary.
1857,	June,	(Letter of September 1, 1857.)
	Depth,	of lava in *basin* of Halemaumau, about 100 feet below its rim.
	Activity,	rather "quiet," for that time.

1858,	August,	
	Depth,	in "deep basin of Halemaumau," not more definitely specified.
	Activity,	sluggish for that time, but there was a molten lake alternately freezing and thawing.
1859-1862,		Summaries by W. T. Brigham and C. H. Hitchcock.
	Depth,	slowly decreasing.
	Activity,	only ordinary; but there was at all times a molten lake in Halemaumau.
1863,	May or June,	Entry by O. H. Gulick in Volcano House Record Book, dated February 2, 1865.
	Depth, Activity,	"For some years past previous to 1863 the most of the fires visible were to be seen at, or in the vicinity of, the lake in the S. W. part of the crater; but in May, or June, 1863, there was an extensive eruption in the northern part of the crater which flowed over perhaps one-third of the whole basin; the fresh lava covering perhaps over a thousand acres."
	October,	
	Depth,	in general, decreased; overflowing onto the "black ledge," but at the central part the depth remained without change.
	Activity,	increased.
1864,		Visited by W. T. Brigham and Horace Mann.
	Depth,	of molten lava about 30 to 50 feet below the rim of Halemaumau.
	Activity,	ordinarily great, for that time.

(B) CHARTS EXHIBITING ACTIVITY AT KILAUEA, 1865–1911.

These observations are arranged in a co-ordinate manner, — with the months of each year set out in order on the axis of abscissas, and the years in sequence, one above another, on the axis of ordinates.

With regard to the semi-annual variation in activity, attention is particularly directed to the times in the *revivals* in activity which occurred during the relatively dormant term from 1895 to 1906. The occurrence of these near solstice is especially striking.

In these charts, in general, for any year the following alignment is employed.

On the upper line appear statements referring to the height of stand or its fluctuations, and on the lower line statements referring to the condition of activity.

Three faces of type are used. For observations which indicate high stand, or notable rising, or great or increasing activity *which appear from all accounts to be particularly well substantiated* black-face type is used, not only when these conditions fall near solstice but *also*, and *especially*, at other times.

Italic-face is used in a similar way to indicate those *particularly well substantiated* observations which indicate falling, or low stand, or slight or decreasing action both around equinox and also at other times especially.

Ordinary type indicates that the observations point to ordinary conditions, considered in relation to the general state of action of the volcano at the time. In making judgment of this especial scrutiny at the critical times of year has been necessary.

In preparing the charts it has been necessary to employ a limited number of phrases only. Thus, for example, the words "very active" occur almost constantly, — and in all three type faces. They have necessarily a different meaning and connotation at different stages of eruption, and their appearance in the different type faces helps to fix this.

It was early seen that this procedure with reference to typography tended strongly to emphasize a *general* correspondence of the observational data with the hypothesis. This is distinctly an advantage unless *the weighing of the evidence*, which has controlled the typographical exhibit, has been faulty or prejudiced. Every effort has been made to avoid this. Doubtless some errors of judgment have entered in, but it is considered that there is no systematic occurrence of these and it is hoped that they affect the work as a whole very little.

Responses, if any, to strain from variation of latitude are difficult to recognize or test by inspection. It is thought, however, that this, combined with the soli-lunar strain, should bring about, at intervals of approximately seven years, the translation of the maximum response from solstice in a given year to later months in the succeeding year or two. Therefore it is interesting to note such tendencies to translation exhibited by these charts, as brought out in the following table. Of course nothing can be proved from so faulty a correlation, but the suggestion referred to in earlier pages is thus brought to notice.

CHART I.

	January	February
1865	**High lava jets seen from Volcano House** **" Most active month for a year past "**	Continues active **Very**
1866	" Tolerably active " Ordinary Quiet	Quiet
1867		**Great activity** **Eight lava-lakes**
1868	**Unusually**	**active**
1869		***Lava fallen very low*** ***Activity slight, very smoky***
1870	Not notably high Activity only slight } by an experienced observer	High, south lake overflowing banks Activity slight
1871	Overflowing in all directions Very active Very active	
1872	Moderately high " Quite active "	
1873	High **" Mauna Loa resumes activity "** Very active Less active Active	**Active to very**
1874		
1875		Down 40 feet, to 20 feet, to overflowing Very active, to less active, to more active
1876	Overflowing (Sharp earthquake) Ordinary activity	Overflowing but wi Mauna Loa active Very active
1877	High Active	" Lava
1878	**Overflowing** Down 40 feet **Very active**	Less active (?)
1879	**High** **Flows through clefts in all directions.** **Very active** **By an experienced observer**	
1880	Overflowing Active Not markedly a	ctive Very active
1881	**Very active**	**Overflowing** **Jets and fountains** **Very active**
1882		
1883		**Activity on**
1884	**Very active** **Jets 100 feet high** **" Pele's hair " in air**	**Very active**
1885	**Active**	**Active**
1886	**High** **and** **Very active**	**rising**
1887	**Mauna Loa in eruption** Comparatively inactive (Earthquakes)	**Only ordinarily active**

CHART 2.

	January	February
1888	Ordinarily active	
1889	Very active	Very active Overflowing Very active
1890		Very active
1891	Violently active	Very active
1892	*Lower* *Less active?* Rising	About 275 feet below surface About 25 feet below black ledge Very active [L. A. Thurston]
1893	Overflowing onto black ledge Black ledge is 125 feet below surface Ordinarily active Rising 100 feet Very active	
1894	Overflowing onto the black ledge Very active Rising	Overflowing onto the bed of the main crater
1895	Complete	
1896	“JAN. 3, 1896, the lava returned to the crater at 11.30 since Dec. 6, 1894,—a longer period of inactivity than from the bottom itself. The lava broke out quietly	p.m. and formed during that night a lake 200 feet E-W any previously recorded. The lava apparently flowed without any previous indication of eruption [so far as
1897		Only sounds of rushing gas
1898	Complete	
1899		
1900	Complete	
1901		
1902	Fresh black lava before this date.	February 14, 1902. at bottom of pit indicating unobserved action a little Peripheral cracks cherry red at night. [L. A. Thurston]
1903	Active lake “as in 1894” W. R. Castle *26 Jan. Not active*	
1904	*10 January lava again disappeared*	
1905		Molten lava fountain, Feb. 22, at bottom of Halemaumau pit
1906	Unusually active	
1907	Jan. 7, Mauna Loa active, flow at S. W. In Kilauea molten lava rising Intermittently very active.	Very
1908	Moderate activity	Rising from depth of 425 feet to 302 feet (actual measurement) Cone and jet activity
1909	High Very active Very active	Lower Very active
1910	Depth less than 100 feet Very active Still overflowing onto black ledge	Subsiding Very active Depth about Very a
1911	Very active	Very active

During	*Tendency to translation of max. volcanic response*		*Character*
	From	*Towards*	
*1866–68	Winter solstice	Spring	Strongly marked
[1871–73]	————	————	Response absent or not well marked
[1872-74]	————	————	Ditto
1878–80	Winter solstice	Spring	Feebly indicated
1879–81	Summer solstice	Autumn	Fairly well marked
1885–[86]	Winter solstice	Spring	Marked, then *breakdown*
[1886–88]	————	————	No discernible evidence
1892–94	Winter solstice	Spring	Marked, then *breakdown*
[1893–95]	————	————	No evidence, dormant
[1899–01]	————	————	No evidence, dormant
[1900]–02	Summer solstice	Autumn	Fairly well marked
[1906–08]	————	————	Not indicated
1907–09	Summer solstice	Autumn	Strongly marked

* This particular crisis may well be due to other causes associated with great overstrain in the region, as pointed out by the writer recently.

(C) CHARTS SHOWING THE STRAIN CURVE,

on which also are indicated the dates of perigee, apogee and lunar phases, and

CORRELATIVE CHARTS,

showing the measured heights of stand of magma in Halemaumau, on which also are indicated observed directions of the rising and falling movement, especially at times of infrequent measurement, and observed crises in activity.

On these charts, the words, maximum of activity, at any indicated date, need no explanation. The word, crisis, means that immediately after the date in question there was an *observable* decrease in surface activity, height of stand (as distinct from the work of measurement), or both. In determining on these things the judgment of observers has entered, but, it is hoped, with a minimum of prejudice. Moreover, many of these observations have been made by persons unfamiliar with the expectable consequences of the hypothesis here developed; and many more have been made at times when the strain curve had not been computed in advance. These observations, consequently, have necessarily been free of any bias.

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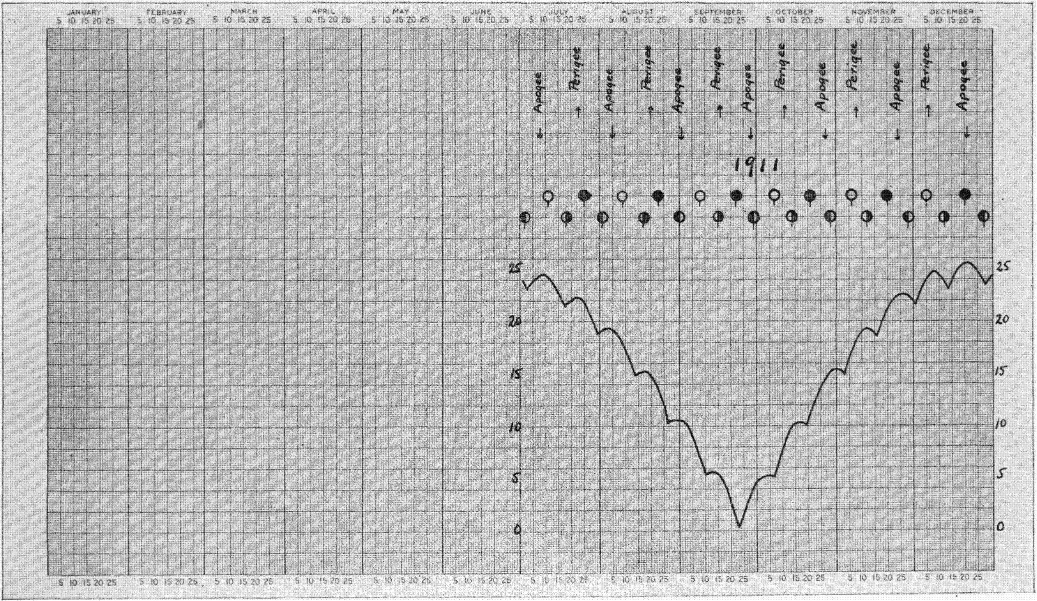
*On the Earthquakes of 1868 in Hawaii. Bull. Seis. Soc. Am. IV, 3.
H. O. Wood, Dec., 1914.


JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
1911
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
25
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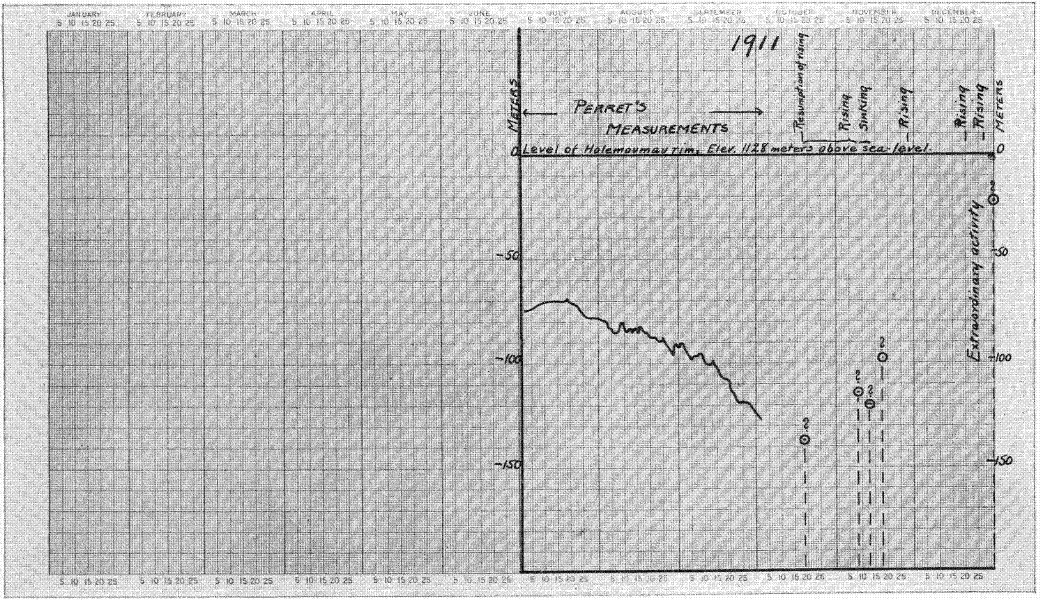
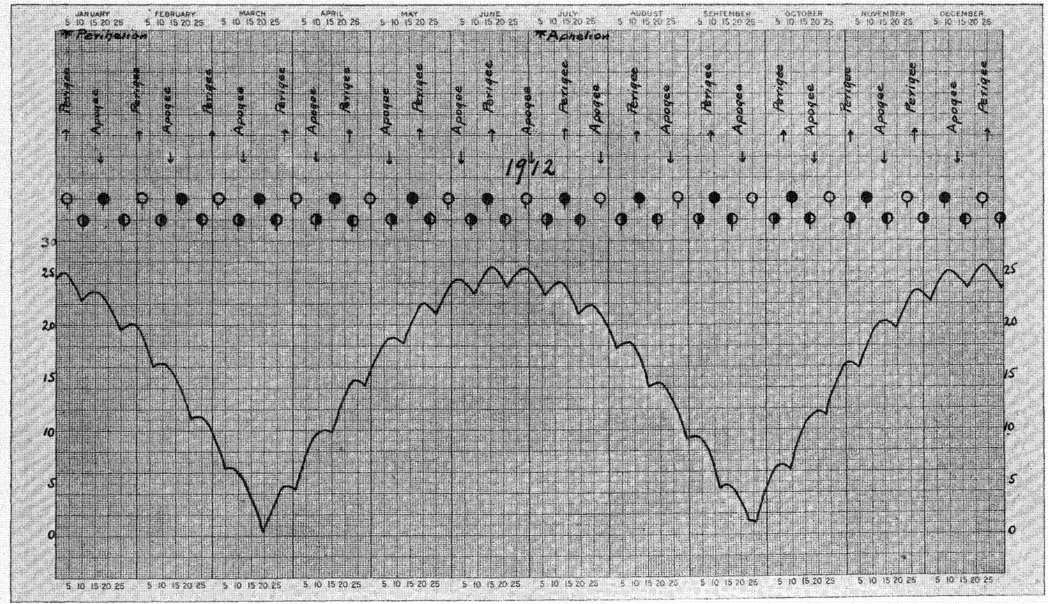

1911
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
PERRET'S MEASUREMENTS
METERS
0 Level of Halemaumau rim, Elev. 1128 meters above sea-level.
-50
-100
-150
Resumption of rising
Rising
Sinking
Rising
Rising
Rising
Extraordinary activity
?


JANUARY
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MARCH
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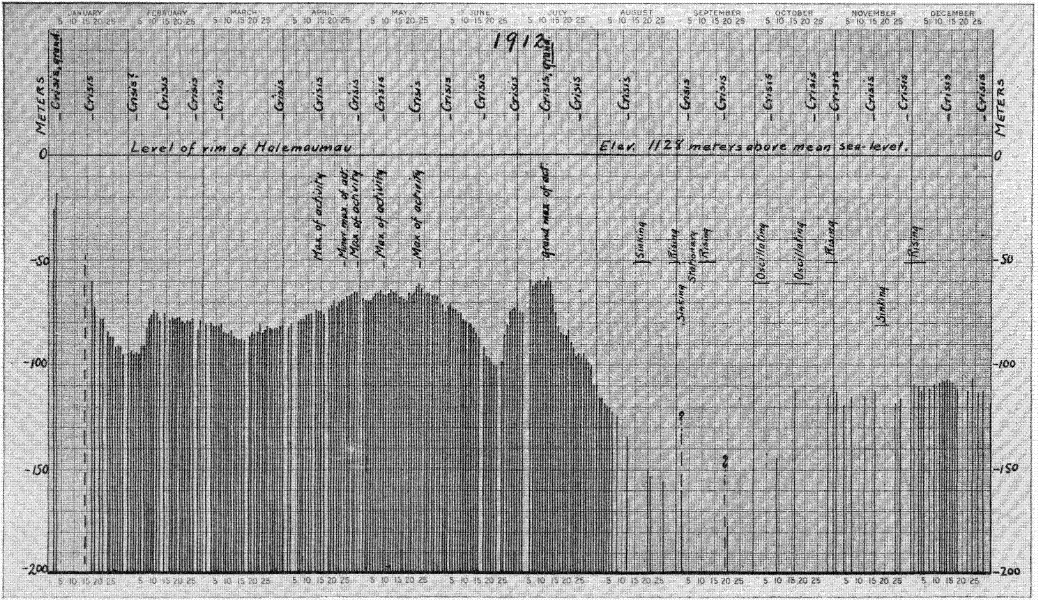
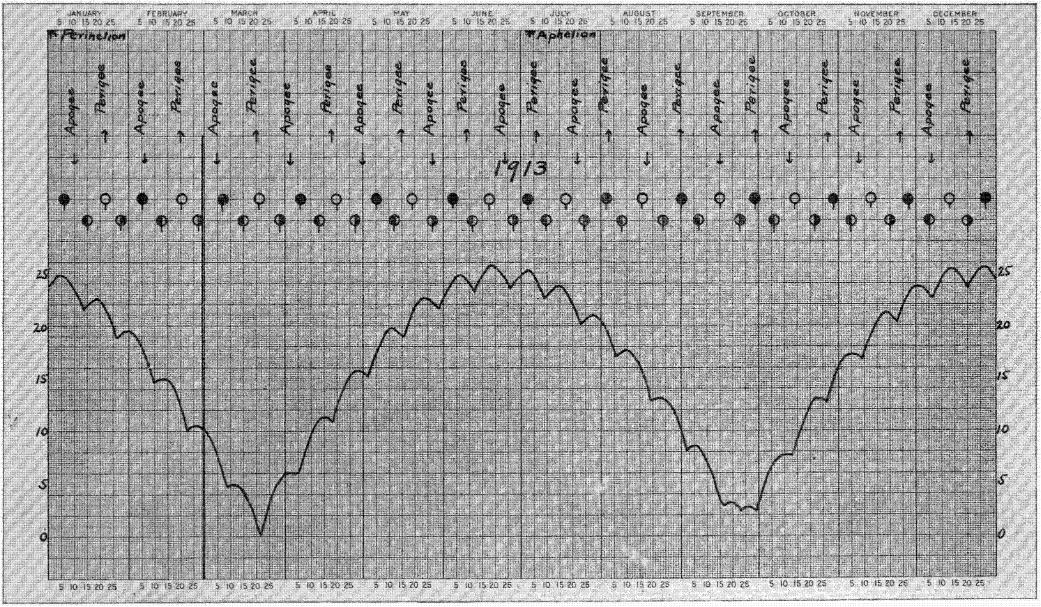
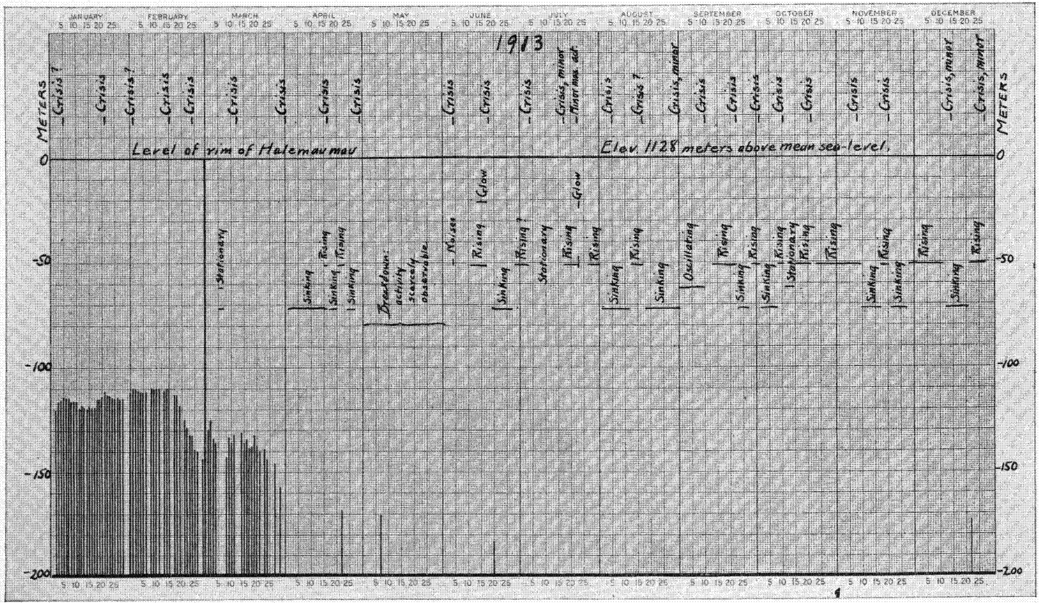
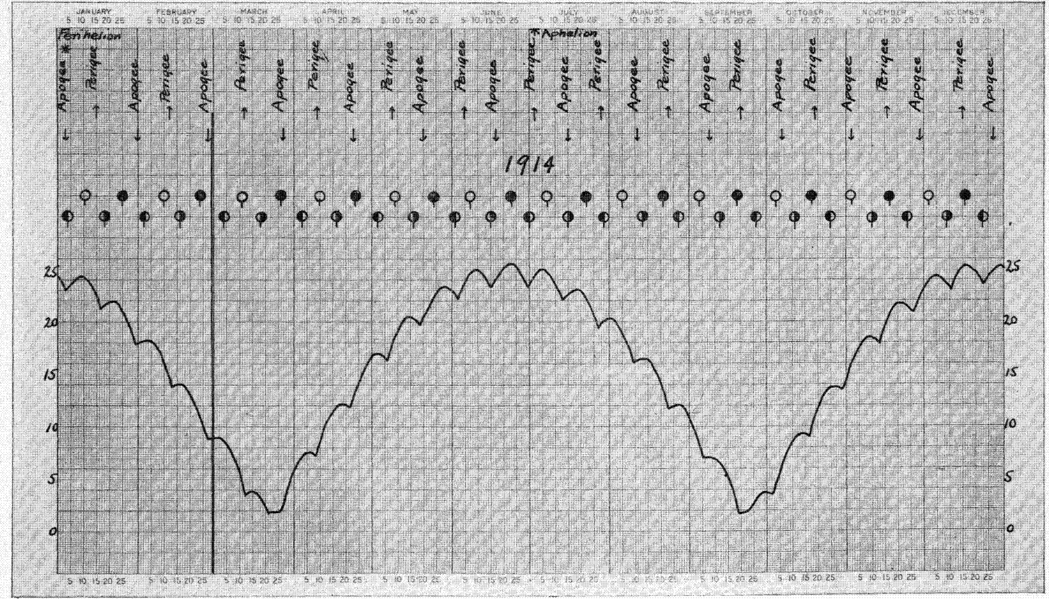
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
Perihelion
Aphelion
Perigee
Apogee
1912
30
25
20
15
10
5
0


1912
METERS
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
Crisis, grand
Crisis
Crisis?
Crisis, grand
Level of rim of Halemaumau
Elev. 1128 meters above mean sea-level.
Max. of activity
Minor max. of act.
Max. of activity
grand max. of act.
Sinking
Rising
Stationary
Rising
Oscillating
Oscillating
Rising
Sinking
Rising
?
0
-50
-100
-150
-200



1913
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
Perihelion
Aphelion
Apogee
Perigee
25
20
15
10
5
0


1913
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
METERS
0
-50
-100
-150
-200
Level of rim of Halemaumau
Elev. 1128 meters above mean sea-level.
-Crisis ?
-Crisis
-Crisis ?
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis, minor
-Minor max. act.
-Crisis
-Crisis ?
-Crisis, minor
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis, minor
-Crisis, minor
Stationary
Sinking
Rising
Sinking
Rising
Sinking
Breakdown: activity scarcely observable.
-Noises
Rising
Glow
Sinking
Rising ?
Stationary
Rising
-Glow
Rising
Sinking
Rising
Sinking
Oscillating
Rising
Sinking
Rising
Sinking
Rising
Stationary
Rising
Rising
Sinking
Rising
Sinking
Rising
Sinking
Rising


1914
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
Perihelion
Aphelion
Apogee *
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee
Apogee
Perigee *
Apogee
Perigee
Apogee
Perigee
Apogee
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Apogee
Perigee
Apogee
Perigee
Apogee
25
20
15
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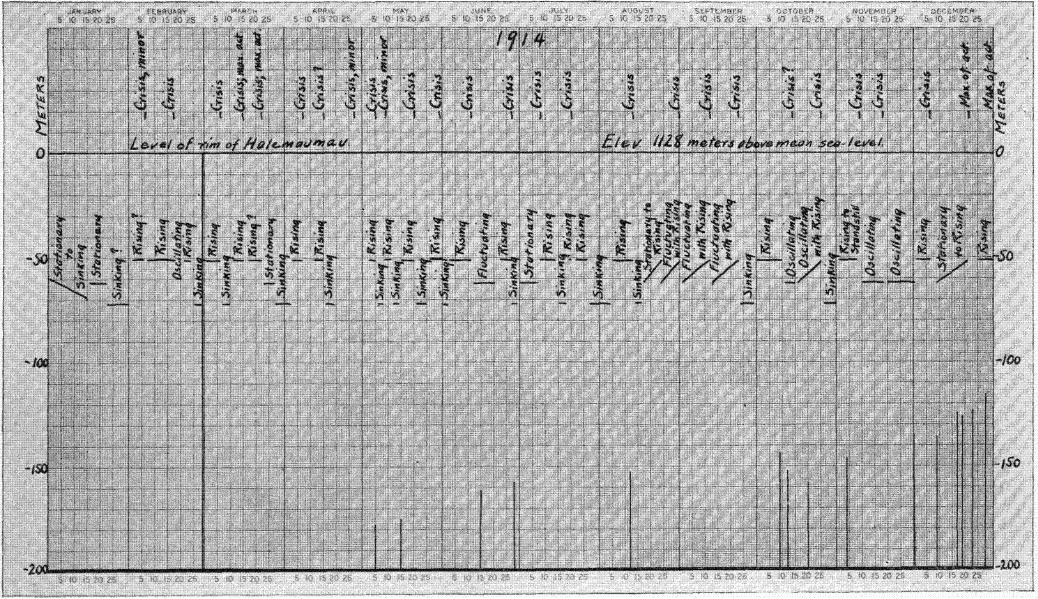
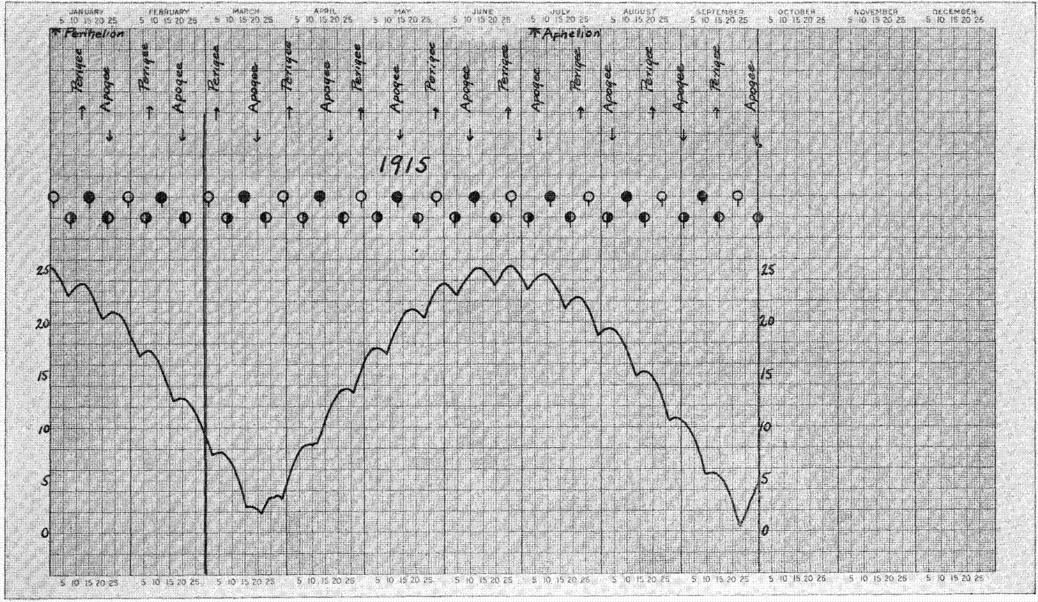

1914
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
METERS
0
-50
-100
-150
-200
Level of rim of Halemaumau
Elev 1128 meters above mean sea-level
-Crisis, minor
-Crisis
-Crisis
-Crisis, max. act
-Crisis, max. act
-Crisis
-Crisis ?
-Crisis, minor
-Crisis
-Crisis, minor
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis
-Crisis ?
-Crisis
-Crisis
-Crisis
-Crisis
-Max. of act
-Max. of act
Stationary to Sinking
Stationary
Sinking ?
Rising ?
Rising
Oscillating
Rising
Sinking
Rising
Sinking
Rising
Rising ?
Stationary
Sinking
Rising
Rising
Sinking
Rising
Sinking
Rising
Sinking
Rising
Sinking
Rising
Sinking
Rising
Sinking
Rising
Fluctuating
Rising
Sinking
Stationary
Rising
Sinking
Rising
Rising
Sinking
Rising
Sinking
Stationary to Rising
Fluctuating with Rising
Fluctuating with Rising
Fluctuating with Rising
Sinking
Rising
Oscillating
Oscillating with Rising
Sinking
Rising to Standstill
Oscillating
Oscillating
Rising
Stationary to Rising
Rising


JANUARY
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5 10 15 20 25
* Perihelion
* Aphelion
Perigee
Apogee
1915
25
20
15
10
5
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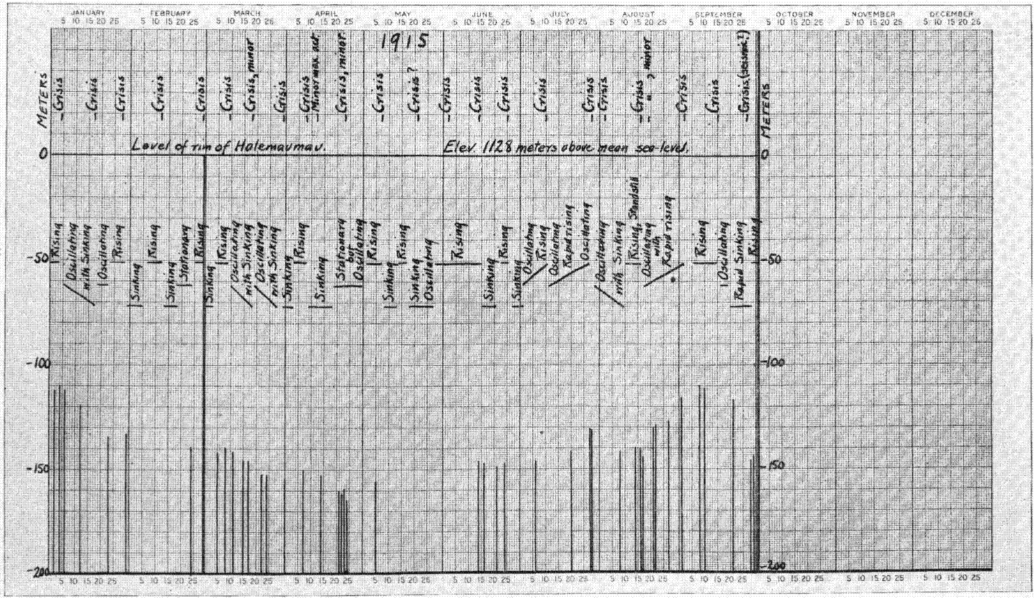
1915
METERS
0
-50
-100
-150
-200
JANUARY
FEBRUARY
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
DECEMBER
5 10 15 20 25
Level of rim of Halemaumau.
Elev. 1128 meters above mean sea-level.
Crisis
Crisis, minor
Minor max. act.
Crisis ?
" , minor
Crisis (seismic ?)
Rising
Oscillating with Sinking
Oscillating
Sinking
Stationary
Stationary but Oscillating
Rising, Standstill
Rapid rising
Rapid Sinking

CONCLUSION.

It is best, on the whole, that these correlations of volcanic evidence with the hypothesis should speak for themselves. For to strive to draw attention to all the important correspondences, or failures to correspond, would take much space and in the end would prove confusing. It is far better, too, that interested readers should go carefully over the correlation and find for themselves its points of strength and weakness.

Still, it is but fair to state that the correspondences between the crises of the strain curve and of the volcanic behavior have been more striking and impressive in the day to day, week to week, and month to month comparisons conducted on the ground, and interpreted through minor changes in action difficult to describe and impossible to express on a plotted curve-diagram than the restricted and formal comparison here undertaken can indicate. Indeed it was the repeated occurrence of such comparatively intangible correspondences which suggested the idea which underlies the hypothesis developed here. Therefore, though it is hoped that the hypothesis may stand, and undergo development and improvement, in any event it has had a clarifying value in guiding the assemblage and reduction to order of the complicated and multitudinous observations of the volcano.

In fine, much confidence has been gained in the judgment that larger semi-annual and smaller semi-monthly variations in activity are realities, and that they are well indicated by such a curve as this, though manifestly complicated by other factors, — one of which may well be parallel with variation of latitude.

Hawaiian Volcano Observatory,
2 October, 1915.

APPENDIX.

Whatever its fate, the hypothesis has been of service to the writer as a guide in the study of Kilauea. With the idea that it may be useful to check against it the variations in volcanic activity elsewhere, whereby for such a purpose a similar computation of strain must be undertaken, the strain almanac computed in this study is here appended to indicate the process by which it was computed, and, incidentally, to permit critical examination of it.

THE STRAIN ALMANAC

DETERMINATION OF PERCENTAGE-MULTIPLIERS

(*) Determination of percentage-multipliers for lunar declination angles to be used in approximating numerical equivalents for lunar, nutational strain. Basis, 28° 00′ 00.0″ ≎ nat. sin. = 0.4695 = 7.5% as slide-rule gage point.

1911—1915

1911

Dates of,	*Fortnightly Max. Ang. Decl.*	*Nat. Sines*	*%*	*% to nearest tenths*
13 January	27° 08′ 10.5″—	0.4561+	=7.28	7.3
27	27° 10′ 45.7″ —	0.4568	=7.30	
9 February	27° 15′ 54.9″—	0.4581−	=7.33	
23	27° 22′ 15.7″—	0.4597+	=7.34	
8 March	27° 28′ 35.4″—	0.4614−	=7.36	7.4
22	27° 34′ 57.9″—	0.4630−	=7.40	
5 April	27° 38′ 57.5″—	0.4641−	=7.42	
19	27° 41′ 45.9″—	0.4648−	=7.43	
2	27° 42′ 08.6″—	0.4648+	=7.43	
16 May	27° 40′ 56.6″—	0.4646−	=7.43−	
29	27° 39′ 21.7″—	0.4642−	=7.42+	
12 June	27° 36′ 54.5″—	0.4636−	=7.41	
26	27° 36′ 25.7″—	0.4634+	=7.41	
10 July	27° 36′ 08.5″—	0.4633+	=7.41−	
23	27° 38′ 58.0″—	0.4641−	=7.42	
6 August	27° 42′ 21.0″—	0.4649+	=7.43+	
19	27° 48′ 00.5″—	0.4664+	=7.45	
2	27° 53′ 34.5″—	0.4678+	=7.48	7.5
16 September	27° 59′ 07.9—	0.4692+	=7.50+	
29	28° 03′ 34.3″—	0.4704−	=7.51	
13 October	28° 06′ 00.1″—	0.4710	=7.52	
27	28° 06′ 37.6″—	0.4712−	=7.52	
9 November	28° 05′ 22.8″—	0.4709−	=7.51	
23	28° 02′ 40.2″—	0.4702−	=7.50+	
7 December	28° 00′ 28.2″—	0.4696−	=7.50+	
20	27° 58′ 02.6″—	0.4690−	=7.49+	

(*) See III, 16-17

1912

Dates of,	*Fortnightly Max. Ang. Decl.*	*Nat. Sines*	%	*% to nearest tenths*
3	27° 58′ 50.0″—	0.4692−	=7.49	
16 January	28° 00′ 01.8″—	0.4695+	=7.50+	
30	28° 05′ 06.4″—	0.4708+	=7.51	7.5
13 February	28° 09′ 37.3″—	0.4719+	=7.53	
27	28° 16′ 06.7″—	0.4736+	=7.56	
11 March	28° 20′ 34.4″—	0.4747+	=7.58	
25	28° 24′ 14.2″—	0.4756+	=7.59	
7 April	28° 25′ 36.7″—	0.4760+	=7.60	
21	28° 24′ 59.2″—	0.4759−	=7.59	
5 May	28° 22′ 55.7″—	0.4754−	=7.59	
19	28° 20′ 05.5″—	0.4746+	=7.58	
1	28° 17′ 03.9″—	0.4738+	=7.56	
15 June	28° 15′ 35.6″—	0.4735−	=7.55+	
28	28° 14′ 38.0″—	0.4732+	=7.55+	7.6
12 July	28° 16′ 55.2″—	0.4738−	=7.56	
25	28° 19′ 10.4″—	0.4743+	=7.57	
9 August	28° 24′ 34.4″—	0.4758−	=7.59	
22	28° 28′ 32.8″—	0.4768−	=7.62	
5 September	28° 33′ 45.7″—	0.4781+	=7.64	
18	28° 36′ 33.2″—	0.4788+	=7.65−	
2	28° 38′ 07.8″—	0.4792+	=7.65−	
15 October	28° 37′ 38.3″—	0.4791−	=7.65−	
30	28° 34′ 59.6″—	0.4784	=7.64	
12 November	28° 31′ 42.5″—	0.4776+	=7.63	
26	28° 27′ 55.5″—	0.4766−	=7.62	
9 December	28° 25′ 03.3″—	0.4759+	=7.60	
23	28° 24′ 26.9″—	0.4755+	=7.59	

1913

Dates of,	Fortnightly Max. Ang. Decl.	Nat. Sines	%	% to nearest tenths
5 January	28° 24′ 54.3″—	0.4759−	=7.59	7.6
20	28° 29′ 02.0″—	0.4769+	=7.61	
1 February	28° 32′ 24.9″—	0.4778−	=7.62	
16	28° 38′ 13.8″—	0.4792+	=7.65−	
1	28° 41′ 24.1″—	0.4800+	=7.66	7.7
15 March	28° 44′ 10.5″—	0.4807+	=7.67	
28	28° 44′ 25.3″— grand max.	0.4808+	=7.68	
12 April	28° 42′ 18.5″—	0.4803−	=7.66	
24	28° 39′ 36.6″—	0.4796+	=7.65+	
9 May	28° 34′ 57.4″—	0.4784−	=7.64	7.6
22	28° 31′ 37.8″—	0.4776−	=7.62	
5 June	28° 28′ 32.3″—	0.4767+	=7.61	
18	28° 27′ 19.1″—	0.4764+	=7.60+	
2	28° 28′ 15.3″—	0.4766+	=7.60	
15 July	28° 30′ 00.0″—	0.4772	=7.62	
30	28° 34′ 14.6″—	0.4782+	=7.64	
11 August	28° 37′ 20.0″—	0.4788	=7.65−	
26	28° 41′ 24.9″—	0.4800+	=7.66	7.7
8 September	28° 43′ 07.1″—	0.4805+	=7.67	
22	28° 43′ 19.3″—	0.4806−	=7.67	
5 October	28° 42′ 01.2″—	0.4802+	=7.66	
20	28° 37′ 42.5″—	0.4791+	=7.65+	
1	28° 34′ 00.4″—	0.4782	=7.64	7.6
16 November	28° 28′ 16.6″—	0.4767−	=7.61	
29	28° 25′ 09.5″—	0.4759	=7.59	
13 December	28° 22′ 36.2″ —	0.4753−	=7.58	
26	28° 22′ 37.8″—	0.4753−	=7.58	

1914

Dates of,	*Fortnightly Max. Ang. Decl.*	*Nat. Sines*	%	*% to nearest tenths*
10 January	28° 25′ 02.6″—	0.4759+	=7.59	7.6
22	28° 27′ 54.4″—	0.4766−	=7.61	
6 February	28° 32′ 09.6″—	0.4777+	=7.62	
19	28° 34′ 30.8″—	0.4783	=7.63	
5 March	28° 35′ 54.1″—	0.4787−	=7.64	
18	28° 35′ 12.8″—	0.4784+	=7.63	
2	28° 31′ 36.0″—	0.4776−	=7.62	
14 April	28° 28′ 08.7″—	0.4766+	=7.61	
29	28° 21′ 48.0″—	0.4751−	=7.58	
12 May	28° 18′ 05.0″—	0.4741+	=7.57	
26	28° 13′ 15.9″—	0.4728+	=7.55+	
8 June	28° 11′ 52.3″—	0.4726−	=7.55+	
22	28° 11′ 08.1″—	0.4723+	=7.55±	
5 July	28° 12′ 40.5″—	0.4727+	=7.55+	
20	28° 15′ 14.5″—	0.4734−	=7.55+	
2	28° 17′ 49.6″—	0.4740+	=7.56+	
16 August	28° 20′ 19.6″—	0.4747−	=7.58	
29	28° 20′ 52.3″—	0.4749−	=7.58	
12 September	28° 20′ 08.6″—	0.4746+	=7.58	
25	28° 17′ 46.9″—	0.4741−	=7.56	
10 October	28° 12′ 17.4″—	0.4726+	=7.55+	
22	28° 07′ 48.3″—	0.4715−	=7.53	7.5
6 November	28° 00′ 44.1″—	0.4696+	=7.50+	
19	27° 57′ 06.0″—	0.4687+	=7.49	
3	27° 52′ 55.3″—	0.4677−	=7.47	
16 December	27° 52′ 42.6″—	0.4677−	=7.47	
30	27° 53′ 11.7″—	0.4677+	=7.47	

1915

Dates of,	*Fortnightly Max. Ang. Decl.*	*Nat. Sines*	%	*% to nearest tenths*
13 January	27° 55′ 41.9″—	0.4683+	=7.48	
27	27° 58′ 10.6″—	0.4690+	=7.49	7.5
9 February	27° 59′ 52.9″—	0.4695−	=7.50−	
23	27° 59′ 55.4″—	0.4695−	=7.50−	
8 March	27° 58′ 06.1″—	0.4690+	=7.49	
22	27° 53′ 35.4″—	0.4678+	=7.47	
4 April	27° 48′ 53.9″—	0.4666−	=7.45	
19	27° 41′ 45.5″—	0.4648−	=7.42	
2	27° 37′ 06.3″—	0.4636+	=7.40	
16 May	27° 31′ 20.1″—	0.4621	=7.38	
29	27° 29′ 24.5″—	0.4615+	=7.37	
12 June	27° 27′ 31.6″—	0.4611+	=7.36	7.4
25	27° 28′ 43.9″—	0.4615−	=7.37	
9 July	27° 29′ 54.4″—	0.4617−	=7.37+	
23	27° 32′ 01.4″—	0.4623	=7.38	
6 August	27° 33′ 09.8″—	0.4625+	=7.39	
19	27° 33′ 04.6″—	0.4625+	=7.39	
2	27° 31′ 08.7″—	0.4620+	=7.38	
15 September	27° 27′ 23.4″—	0.4610+	=7.36	
29	27° 21′ 36.1″—	0.4596−	=7.34	
13 October	27° 15′ 38.4″—	0.4580+	=7.31	7.3
26	27° 08′ 22.4″—	0.4561+	=7.28	
9 November	27° 03′ 35.8″—	0.4549+	=7.26	
23	26° 58′ 47.2″—	0.4537−	=7.24	
6 December	26° 57′ 48.2″—	0.4535−	=7.24	7.2
20	26° 57′ 10.7″—	0.4532+	=7.23	

COMPUTATION OF THE STRAIN EQUIVALENTS

N. B.— The computation for a single year will suffice to illustrate the method and the properties of the semi-annual variation. The year 1913 is as instructive as any.

1913

JANUARY

	Sun S		Moon			*Moon direct angles*		Strain	Equivalents
1	23.04	+	1.05	=	*7.6%*	*S 13.78*	=	**24.1**	
2	22.95	+	1.45	=		*19.02*	=	**24.4**	
3	22.86	+	1.77			*23.29*	=	**24.6**	
4	22.76	+	2.00			*26.37*	=	**24.8**	
5	22.65	+	2.14			*28.08*	=	**24.8**	
6	22.54	+	2.16	=		*28.35*	=	**24.7**	● **Spring tides**
7	22.42	+	2.07	=		*27.20*	=	**24.5**	
8	22.29	+	1.88	=		*24.78*	=	**24.2**	
9	22.15	+	1.62	=		*21.31*	=	**23.8**	
10	22.01	+	1.29	=		*16.99*	=	**23.3**	× **Apogee**
11	21.86	+	0.92	=		*12.07*	=	**22.8**	
12	21.70	+	0.51	=		*6.71*	=	**22.2**	
13	21.53	+	0.08	=		S *1.10*	=	**21.6**	
14	21.36	+	0.35	=		N *4.62*	=	**21.7**	
15	21.18	+	0.78	=		*10.27*	=	**22.0**	☽ **Neap tides**
16	20.99	+	1.19	=		*15.67*	=	**22.2**	
17	20.81	+	1.56	=		*20.56*	=	**22.4**	
18	20.61	+	1.87	=		*24.60*	=	**22.5**	
19	20.40	+	2.08	=		*27.38*	=	**22.5**	
20	20.19	+	2.17	=		*28.48*		**22.4**	
21	19.97	+	2.10	=		*27.60*		**22.1**	{ × **Perigee**
22	19.83	+	1.88	=		*24.72*	=	**21.7**	{ ○ **Spring tides**
23	19.52	+	1.53	=		*20.08*	=	**21.1**	
24	19.28	+	1.08	=		*14.15*		**20.4**	
25	19.04	+	0.57	=		*7.47*	=	**19.6**	
26	18.79	+	0.04	=		*N 0.52*	=	**18.8**	
27	18.54	+	0.48			*S 6.27*	=	**19.0**	
28	18.28	+	0.95	=		*12.57*	=	**19.2**	☾ **Neap tides**
29	18.01	+	1.38	=		*18.10*	=	**19.4**	
30	17.74	+	1.72	=		*22.64*	=	**19.5**	
31	17.47	+	1.97	=	*7.6%*	*S 25.98*	=	**19.4**	
	S **Sun**		**Moon**						

FEBRUARY

	Sun S		Moon			*Moon direct angles*		Strain	Equivalents
1	17.19	+	2.08	=	*7.6%*	*S 27.97*	=	**19.3**	
2	16.90	+	2.17	=		*28.53*	=	**19.1**	
3	16.61	+	2.11	=		*27.69*	=	**18.7**	
4	16.32	+	1.94	=		*25.55*	=	**18.3**	
5	16.02	+	1.70	=		*22.30*	=	**17.7**	● **Spring tides**
6	15.71	+	1.38	=		*18.15*	=	**17.1**	× **Apogee**
7	15.40	+	1.02	=		*13.33*	=	**16.4**	
8	15.09	+	0.61	=		*8.03*	=	**15.7**	
9	14.77	+	0.19	=		*S 2.44*	=	**15.0**	
10	14.45	+	0.25	=		*N 3.26*	=	**14.7**	
11	14.12	+	0.68	=		*8.92*	=	**14.8**	
12	13.79	+	1.09	=		*14.33*	=	**14.9**	
13	13.46	+	1.47	=		*19.30*	=	**14.9**	☽ **Neap tides**
14	13.12	+	1.79	=		*23.53*	=	**14.9**	
15	12.78	+	2.03	=		*26.70*	=	**14.8**	
16	12.41	+	2.16	=		*28.42*	=	**14.6**	
17	12.09	+	2.16	=		*28.38*	=	**14.3**	
18	11.74	+	2.01	=		*26.39*	=	**13.8**	
19	11.38	+	1.71	=		*22.52*	=	**13.1**	{ × **Perigee**
20	11.03	+	1.36	=		*17.88*	=	**12.4**	{ ○ **Spring tides**
21	10.67	+	0.80	=		*10.56*	=	**11.5**	
22	10.31	+	0.26	=	*7.6%*	*N 3.47*	=	**10.6**	
23	9.94	+	0.28	=	*7.7%*	*S 3.70*	=	**10.2**	
24	9.57	+	0.81	=		*10.49*	=	**10.4**	
25	9.20	+	1.28	=		*16.56*	=	**10.5**	
26	8.83	+	1.66	=		*21.59*	=	**10.5**	
27	8.46	+	1.95	=		*25.38*	=	**10.4**	☾ **Neap tides**
28	8.09	+	2.14	=	*7.7%*	*27.16*	=	**10.2**	
	S **Sun**		**Moon**						

MARCH

	Sun S	Moon		Moon *direct angles*	Strain Equivalents	
1	7.71	+ 2.21 =	*7.7%*	*S 28.68* =	**9.9**	
2	7.32	+ 2.17 =		*28.15* =	**9.5**	
3	6.94	+ 2.03 =		*26.29* =	**9.0**	
4	6.56	+ 1.79 =		*23.28* =	**8.4**	
5	6.17	+ 1.49 =		*19.32* =	**7.7**	× **Apogee**
6	5.78	+ 1.13 =		*14.63* =	**6.9**	
7	5.38	+ 0.72 =		*9.40* =	**6.1**	● **Spring tides**
8	5.01	+ 0.30 =		*S 3.83* =	**5.3**	
9	4.62	+ 0.15 =		*N 1.91* =	**4.8**	
10	4.23	+ 0.59 =		*7.64* =	**4.8**	
11	3.84	+ 1.01 =		*13.15* =	**4.9**	
12	3.44	+ 1.40 =		*18.23* =	**4.8**	
13	3.05	+ 1.74 =		*22.64* =	**4.8**	
14	2.66	+ 2.01 =		*26.06* =	**4.7**	
15	2.26	+ 2.17 =		*28.18* =	**4.4**	☽ **Neap tides**
16	1.87	+ 2.21 =		*28.70* =	**4.1**	
17	1.47	+ 2.12 =		*27.44* =	**3.6**	
18	1.08	+ 1.87 =		*24.37* =	**3.0**	
19	0.68	+ 1.51 =		*19.67* =	**2.2**	
20	S 0.28	+ 1.05 =		*13.69* =	**1.3**	× **Perigee**
21	N 0.01	+ 0.53 =		*N 6.84* =	**0.5**	○ **Spring tides**
22	0.51	+ 0.03 =		*S 0.37* =	**0.5**	
23	0.90	+ 0.58 =		*7.49* =	**1.5**	
24	1.29	+ 1.08 =		*14.08* =	**2.4**	
25	1.69	+ 1.52 =		*19.75* =	**3.2**	
26	2.08	+ 1.86 =		*24.19* =	**3.9**	
27	2.47	+ 2.09 =		*27.18* =	**4.6**	
28	2.86	+ 2.20 =		*28.61* =	**5.1**	
29	3.25	+ 2.19 =		*28.49* =	**5.4**	☾ **Neap tides**
30	3.64	+ 2.08 =		*26.97* =	**5.7**	
31	4.30	+ 1.87 =	*7.7%*	*S 24.23* =	**6.2**	
	N Sun	Moon				

APRIL

	Sun N	Moon		Moon *direct angles*	Strain Equivalents	
1	4.42	+ 1.58 =	*7.7%*	*S 20.49* =	**6.0**	
2	4.80	+ 1.23 =		*15.97* =	**6.0**	× **Apogee**
3	5.19	+ 0.84 =		*10.87* =	**6.0**	
4	5.57	+ 0.41 =		*S 5.36* =	**6.0**	
5	5.95	+ 0.08 =		*N 0.36* =	**6.0**	
6	6.33	+ 0.47 =		*6.15* =	**6.8**	● **Spring tides**
7	6.71	+ 0.91 =		*11.78* =	**7.6**	
8	7.08	+ 1.31 =		*17.04* =	**8.3**	
9	7.46	+ 1.67 =		*21.67* =	**9.1**	
10	7.83	+ 1.95 =		*25.36* =	**9.8**	
11	8.20	+ 2.14 =		*27.79* =	**10.3**	
12	8.57	+ 2.21 =		*28.70* =	**10.8**	
13	8.93	+ 2.15 =		*27.91* =	**11.1**	☽ **Neap tides**
14	9.29	+ 1.95 =		*25.39* =	**11.2**	
15	9.65	+ 1.64 =		*21.30* =	**11.3**	
16	10.00	+ 1.22 =		*15.90* =	**11.2**	
17	10.36	+ 0.73 =		*9.55* =	**11.1**	
18	10.71	+ 0.20 =		*N 2.63* =	**10.9**	× **Perigee**
19	11.06	+ 0.34 =		*S 4.44* =	**11.4**	
20	11.41	+ 0.87 =		*11.25* =	**12.3**	○ **Spring tides**
21	11.75	+ 1.34 =		*'17.37* =	**13.1**	
22	12.09	+ 1.73 =		*22.42* =	**13.8**	
23	12.42	+ 2.01		*26.08* =	**14.4**	
24	12.75	+ 2.17 =		*28.18* =	**14.9**	
25	13.08	+ 2.20 =		*28.62* =	**15.3**	
26	13.41	+ 2.12 =		*27.54* =	**15.5**	
27	13.73	+ 1.94 =		*25.14* =	**15.7**	☾ **Neap tides**
28	14.05	+ 1.67 =		*21.66* =	**15.7**	
29	14.36	+ 1.33 =		*17.33* =	**15.7**	
30	14.67	+ 0.95 =	*7.7%*	*12.38* =	**15.6**	× **Apogee**
	N Sun	Moon				

MAY

	Sun N		Moon			Moon *direct angles*		Strain	Equivalents
1	14.98	+	0.54	=	*7.7*	*S 6.99*	=	**15.5**	
2	15.28	+	0.11	=	*7.7*	*S 1.34*	=	**15.4**	
3	15.58	+	0.34	=	*7.6*	*N 4.43*	=	**15.9**	
4	15.87	+	0.77	=		*10.14*	=	**16.6**	
5	16.16	+	1.19			*15.56*	=	**17.4**	● **Spring tides**
6	16.45	+	1.55	=		*20.43*	=	**18.0**	
7	16.73	+	1.86	=		*24.43*	=	**18.6**	
8	17.00	+	2.07			*27.23*	=	**19.1**	
9	17.27	+	2.17	=		*28.52*	=	**19.4**	
10	17.54	+	2.14	=		*28.11*	=	**19.7**	
11	17.80	+	1.97	=		*25.96*	=	**19.8**	
12	18.05	+	1.69	=		*22.23*	=	**19.7**	☽ **Neap tides**
13	18.30	+	1.31	=		*17.21*	=	**19.6**	
14	18.55	+	0.85	=		*11.22*	=	**19.4**	
15	18.79	+	0.35	=		*4.64*	=	**19.1**	× **Perigee**
16	19.03	+	0.17	=		*N 2.20*	=	**19.2**	
17	19.26	+	0.68	=		*S 8.93*	=	**19.9**	
18	19.48	+	1.15	=		*15.17*	=	**20.6**	
19	19.70	+	1.56	=		*20.56*	=	**21.3**	○ **Spring tides**
20	19.92	+	1.88	=		*24.74*	=	**21.8**	
21	20.12	+	2.09	=		*27.44*	=	**22.2**	
22	20.16	+	2.17	=		*28.51*	=	**22.3**	
23	20.52	+	2.13	=		*27.97*	=	**22.7**	
24	20.71	+	1.97	=		*25.97*	=	**22.7**	
25	20.89	+	1.74	=		*22.78*	=	**22.6**	
26	21.07	+	1.42	=		*18.67*	=	**22.5**	☾ **Neap tides**
27	21.25	+	1.06	=		*13.88*	=	**22.3**	× **Apogee**
28	21.41	+	0.66	=		*8.62*	=	**22.1**	
29	21.57	+	0.23	=		*S 3.06*	=	**21.8**	
30	21.73	+	0.20	=		*N 2.67*	=	**21.9**	
31	21.87	+	0.64	=	7.6%	*N 8.35*	=	**22.5**	
	N Sun		**Moon**						

JUNE

	Sun N		Moon			Moon *direct angles*		Strain	Equivalents
1	22.01	+	1.05	=	7.6%	*N 13.85*	=	**23.1**	
2	22.15	+	1.44	=		*18.91*	=	**23.6**	
3	22.28	+	1.77	=		*23.23*	=	**24.1**	
4	22.40	+	2.02	=		*26.45*	=	**24.4**	● **Spring tides**
5	22.52	+	2.15	=		*28.23*	=	**24.7**	
6	22.63	+	2.15	=		*28.27*	=	**24.9**	
7	22.73	+	2.02	=		*26.51*	=	**24.8**	
8	22.83	+	1.76	=		*23.07*	=	**24.6**	
9	22.92	+	1.39	=		*18.24*	=	**24.3**	× **Perigee**
10	22.99	+	0.94	=		*12.41*	=	**23.9**	
11	23.07	+	0.45	=		*N 5.96*	=	**23.5**	☽ **Neap tides**
12	23.15	+	0.06	=		*S 0.75*	=	**23.2**	
13	23.20	+	0.56	=		*7.39*	=	**23.8**	
14	23.26	+	1.04	=		*13.63*	=	**24.3**	
15	23.31	+	1.45	=		*19.13*	=	**24.8**	
16	23.35	+	1.79	=		*23.59*	=	**25.2**	
17	23.38	+	2.03	=		*26.71*	=	**25.4**	
18	23.41	+	2.15	=		*28.28*	=	**25.6**	○ **Spring tides**
19	23.43	+	2.15	=		*28.24*	=	**25.6**	
20	23.44	+	2.03	=		*26.68*	=	**25.5**	
21	23.45	+	1.81	=		*23.83*	=	**25.3**	
22	23.45	+	1.52	=		*19.95*	=	**25.0**	
23	23.45	+	1.17	=		*15.32*	=	**24.6**	
24	23.43	+	0.77	=		*10.17*	=	**24.2**	× **Apogee**
25	23.41	+	0.36			*S 4.69*	=	**23.8**	
26	23.38	+	0.07	=		*N 0.96*	=	**23.5**	☾ **Neap tides**
27	23.35	+	0.50	=		*6.62*	=	**23.9**	
28	23.31	+	0.94	=		*12.13*	=	**24.3**	
29	23.26	+	1.32	=		*17.30*	=	**24.6**	
30	23.21	+	1.66	=	7.6%	*N 21.86*	=	**24.9**	
	N Sun		**Moon**						

JULY

	Sun N		Moon		*Moon* *direct angles*		Strain Equivalents	
1	23.15	+	1.94	=	*7.6% N 25.48*	=	**25.1**	
2	23.08	+	2.12	=	*27.79*	=	**25.2**	
3	23.00	+	2.16	=	*28.45*	=	**25.2**	● **Spring tides**
4	22.92	+	2.08	=	*27.76*	=	**25.0**	
5	22.84	+	1.74	=	*24.23*	=	**24.6**	
6	22.74	+	1.49	=	*19.64*	=	**24.2**	× **Perigee**
7	22.64	+	1.05	=	*13.87*	=	**23.7**	
8	22.53	+	0.56	=	*7.38*	=	**23.1**	
9	22.42	+	0.04	=	*N 0.58*	=	**22.5**	
10	22.29	+	0.46	=	*S 6.10*	=	**22.8**	☽ **Neap tides**
11	22.17	+	0.95	=	*12.49*	=	**23.1**	
12	22.03	+	1.38	=	*18.13*	=	**23.4**	
13	21.90	+	1.73	=	*22.77*	=	**23.6**	
14	21.75	+	2.00	=	*26.16*	=	**23.8**	
15	21.60	+	2.14	=	*28.08*	=	**23.7**	
16	21.44	+	2.17	=	*28.44*	=	**23.6**	
17	21.27	+	2.08	=	*27.28*	=	**23.3**	○ **Spring tides**
18	21.01	+	1.88	=	*24.76*	=	**22.9**	
19	20.93	+	1.61	=	*21.15*	=	**22.5**	
20	20.75	+	1.27	=	*16.69*	=	**22.0**	
21	20.56	+	0.89	=	*11.64*	=	**21.5**	
22	20.36	+	0.47	=	*6.22*	=	**20.8**	× **Apogee**
23	20.16	+	0.05	=	*S 0.60*	=	**20.2**	
24	19.96	+	0.38	=	*N 5.05*	=	**20.3**	
25	19.75	+	0.78	=	*10.57*	=	**20.5**	☾ **Neap tides**
26	19.53	+	1.20	=	*15.80*	=	**20.7**	
27	19.31	+	1.56	=	*20.50*	=	**20.9**	
28	19.08	+	1.86	=	*24.42*	=	**20.9**	
29	18.85	+	2.07	=	*27.21*	=	**20.9**	
30	18.61	+	2.17	=	*28.51*	=	**20.8**	
31	18.37	+	2.16	=	*7.6% N 28.47*	=	**20.5**	
	N Sun		Moon					

AUGUST

	Sun N		Moon		*Moon* *direct angles*		Strain Equivalents	
1	18.12	+	2.06	=	*7.6% N 25.70*	=	**20.2**	
2	17.87	+	1.64	=	*21.59*	=	**19.5**	● **Spring tides**
3	17.61	+	1.22	=	*16.05*	=	**18.8**	× **Perigee**
4	17.35	+	0.73	=	*9.56*	=	**18.1**	
5	17.08	+	0.20	=	*N 2.57*	=	**17.3**	
6	16.81	+	0.34	=	*S 4.45*	=	**17.2**	
7	16.54	+	0.85	=	*11.10*	=	**17.4**	
8	16.25	+	1.30	=	*17.05*	=	**17.6**	☽ **Neap tides**
9	15.97	+	1.67	=	*22.00*	=	**17.6**	
10	15.68	+	1.95	=	*25.69*	=	**17.6**	
11	15.39	+	2.12	=	*27.93*	=	**17.5**	
12	15.09	+	2.18	=	*28.62*	=	**17.3**	
13	14.79	+	2.12	=	*27.80*	=	**16.9**	
14	14.48	+	1.95	=	*25.59*	=	**16.4**	
15	14.17	+	1.69	=	*22.23*	=	**15.9**	
16	13.86	+	1.37	=	*17.96*	=	**15.2**	○ **Spring tides**
17	13.55	+	0.99	=	*13.03*	=	**14.5**	
18	13.23	+	0.58	=	*7.67*	=	**13.8**	× **Apogee**
19	12.90	+	0.15	=	*7.6% S 2.06*	=	**13.1**	
20	12.58	+	0.28	=	*7.7% N 3.60*	=	**12.9**	
21	12.25	+	0.70	=	*9.17*	=	**13.0**	
22	11.91	+	1.11	=	*14.46*	=	**13.0**	
23	11.58	+	1.48	=	*19.28*	=	**13.1**	
24	11.23	+	1.80	=	*23.40*	=	**13.0**	☾ **Neap tides**
25	10.90	+	2.02	=	*26.52*	=	**12.9**	
26	10.55	+	2.16	=	*28.35*	=	**12.7**	
27	10.20	+	2.18	=	*28.57*	+	**12.4**	
28	9.85	+	2.08	=	*27.00*	=	**11.9**	
29	9.49	+	1.82	=	*23.64*	=	**11.3**	
30	9.13	+	1.48	=	*18.68*	=	**10.6**	{ × **Perigee**
31	8.78	+	0.96	=	*7.7% N 12.47*	=	**9.7**	{ ● **Spring tides**
	N Sun		Moon					

SEPTEMBER

	Sun N		Moon			*Moon* *direct angles*		Strain	Equivalents
1	8.42	+	0.42	=	*7.7%*	*N 5.49*	=	8.8	
2	8.05	+	0.14	=		*S 1.77*	=	8.2	
3	7.69	+	0.68			*8.85*	=	8.3	
4	7.32	+	1.17	=		*15.31*	=	8.5	
5	6.95	+	1.59	=		*20.77*	=	8.5	
6	6.58	+	1.92	=		*24.93*	=	8.5	
7	6.20	+	2.10	=		*27.62*	=	8.3	☽ Neap tides
8	5.83	+	2.20	=		*28.69*	=	8.0	
9	5.45	+	2.18	=		*28.21*	=	7.6	
10	5.08	+	2.02	=		*26.30*	=	7.1	
11	4.70	+	1.78	=		*23.19*	=	6.5	
12	4.31	+	1.47	=		*19.13*	=	5.8	
13	3.93	+	1.10	=		*14.35*	=	5.0	
14	3.55	+	0.60	=		*9.08*	=	4.2	× Apogee
15	3.17	+	0.27	=		*S 3.51*	=	3.4	● Spring tides
16	2.78	+	0.17	=		*N 2.18*	=	3.0	
17	2.39	+	0.59	=		*7.81*	=	2.9	
18	2.00	+	1.00	=		*13.19*	=	3.0	
19	1.62	+	1.39	=		*18.14*	=	3.0	
20	1.23	+	1.72	=		*22.44*	=	3.0	
21	0.84	+	1.98	=		*25.81*	=	2.8	
22	0.45	+	2.14	=		*27.99*	=	2.7	
23	0.06	+	2.20	=		*28.72*	=	2.3	☾ Neap tides
24	0.33	+	2.14	=		*27.80*	=	2.5	
25	0.72	+	1.98	=		*25.18*	=	2.7	
26	1.11	+	1.69	=		*20.95*	=	2.7	
27	1.50	+	1.18	=		*15.35*	=	2.7	
28	1.89	+	0.67	=		*8.75*	=	2.6	× Perigee
29	2.28	+	0.12	=		*N 1.58*	=	2.4	○ Spring tides
30	2.67	+	0.44	=	*7.7%*	*S 5.71*	=	3.1	
	S Sun		Moon						

OCTOBER

	Sun S		Moon			*Moon* *direct angles*		Strain	Equivalents
1	3.05	+	0.97	=	*7.7%*	*S 12.63*	=	4.0	
2	3.45	+	1.44	=		*18.71*	=	4.9	
3	3.83	+	1.81	=		*23.56*	=	5.6	
4	4.22	+	2.06	=		*26.88*	=	6.3	
5	4.61	+	2.19	=		*28.52*	=	6.8	
6	4.99	+	2.19	=		*28.48*	=	7.2	☽ Neap tides
7	5.37	+	2.06	=		*26.92*	=	7.4	
8	5.76	+	1.85	=		*24.07*	=	7.6	
9	6.14	+	1.55	=		*20.22*	=	7.7	
10	6.52	+	1.20	=		*15.61*	=	7.7	
11	6.89	+	0.80	=		*10.46*	=	7.7	
12	7.28	+	0.38	=		*S 4.97*	=	7.7	× Apogee
13	7.65	+	0.05	=		*N 0.70*	=	7.7	
14	8.02	+	0.49	=		*6.36*	=	8.5	○ Spring tides
15	8.40	+	0.91	=		*11.85*	=	9.3	
16	8.77	+	1.30	=		*16.95*	=	10.1	
17	9.13	+	1.65	=		*21.43*	=	10.8	
18	9.50	+	1.92	=		*25.05*	=	11.4	
19	9.87	+	2.11	=		*27.52*	=	12.0	
20	10.23	+	2.20	=		*28.00*	=	12.4	
21	10.58	+	2.16	=		*28.11*	=	12.7	
22	10.94	+	2.00	=		*26.00*	=	13.1	☾ Neap tides
23	11.29	+	1.72	=		*22.37*	=	13.0	
24	11.65	+	1.33	=		*17.39*	=	13.0	
25	11.99	+	0.87	=		*11.35*	=	12.9	
26	12.34	+	0.35	=	*7.7%*	*N 4.58*	=	12.7	
27	12.68	+	0.19	=	*7.6%*	*S 2.53*	=	12.9	× Perigee
28	13.02	+	0.72	=		*9.55*	=	13.7	
29	13.35	+	1.22	=		*16.03*	=	14.6	● Spring tides
30	13.68	+	1.63	=		*21.51*	=	15.3	
31	14.01	+	1.94	=	*7.6%*	*S 25.57*	=	16.0	
	S Sun		Moon						

NOVEMBER

	Sun S		Moon			*Moon* *direct angles*		Strain Equivalents	
1	14.34	+	2.12	=	*7.6%*	*S 27.95*	=	**16.5**	
2	14.66	+	2.16	=		*28.54*	=	**16.8**	
3	14.97	+	2.09	=		*27.46*	=	**17.1**	
4	15.28	+	1.90	=		*24.95*	=	**17.1**	
5	15.59	+	1.62	=		*21.33*	=	**17.2**	☽ **Neap tides**
6	15.90	+	1.27	=		*16.88*	=	**17.2**	
7	16.19	+	0.90	=		*11.85*	=	**17.1**	
8	16.49	+	0.49	=		*6.45*	=	**17.0**	× **Apogee**
9	16.78	+	0.06	=		*S 0.84*	=	**16.8**	
10	17.06	+	0.36	=		*N 4.81*	=	**17.4**	
11	17.35	+	0.79	=		*10.35*	=	**18.1**	
12	17.62	+	1.19	=		*15.57*	=	**18.8**	
13	17.89	+	1.56	=		*20.26*	=	**19.5**	○ **Spring tides**
14	18.15	+	1.83	=		*24.13*	=	**20.0**	
15	18.42	+	2.04	=		*26.92*	=	**20.5**	
16	18.67	+	2.15	=		*28.34*	=	**20.8**	
17	18.92	+	2.14	=		*28.19*	=	**21.1**	
18	19.16	+	2.01	=		*26.43*	=	**21.2**	
19	19.50	+	1.76	=		*23.14*	=	**21.3**	
20	19.63	+	1.41	=		*18.54*	=	**21.0**	☾ **Neap tides**
21	19.86	+	0.98	=		*12.90*	=	**20.8**	
22	20.08	+	0.50	=		*N 6.53*	=	**20.6**	
23	20.29	+	0.02	=		*S 0.25*	=	**20.3**	
24	20.50	+	0.54	=		*7.08*	=	**21.0**	× **Perigee**
25	20.70	+	1.03	=		*13.60*	=	**21.7**	
26	20.89	+	1.47	=		*19.37*	=	**22.4**	
27	21.08	+	1.82	=		*23.97*	=	**22.9**	● **Spring tides**
28	21.26	+	2.06	=		*27.05*	=	**23.3**	
29	21.44	+	2.15	=		*28.37*	=	**23.6**	
30	21.61	+	2.12	=	*7.6%*	*S 27.93*	=	**23.7**	
	S **Sun**		**Moon**						

DECEMBER

	Sun S		Moon			*Moon* *direct angles*		Strain Equivalents	
1	21.77	+	1.97	=	*7.6%*	*S 25.87*	=	**23.7**	
2	21.92	+	1.71	=		*22.53*	=	**23.6**	
3	22.07	+	1.39	=		*18.26*	=	**23.5**	
4	22.21	+	1.01	=		*13.34*	=	**23.2**	
5	22.34	+	0.60	=		*8.00*	=	**22.9**	☽ **Neap tides**
6	22.47	+	0.19	=		*S 2.45*	=	**22.7**	× **Apogee**
7	22.59	+	0.24	=		*N 3.19*	=	**22.8**	
8	22.70	+	0.66	=		*8.73*	=	**23.4**	
9	22.80	+	1.07	=		*14.03*	=	**23.9**	
10	22.90	+	1.43	=		*18.88*	=	**24.3**	
11	22.99	+	1.77	=		*23.03*	=	**24.8**	
12	23.07	+	1.99	=		*26.17*	=	**25.1**	
13	23.14	+	2.13	=		*28.00*	=	**25.3**	○ **Spring tides**
14	23.21	+	2.15	=		*28.28*	=	**25.4**	
15	23.27	+	2.04	=		*26.89*	=	**25.3**	
16	23.31	+	1.81	=		*23.87*	=	**25.1**	
17	23.36	+	1.48	=		*19.47*	=	**24.8**	
18	23.39	+	1.06	=		*13.98*	=	**24.5**	
19	23.42	+	0.59	=		*7.76*	=	**24.0**	
20	23.44	+	0.09	=		*N 1.13*	=	**23.5**	☾ **Neap tides**
21	23.45	+	0.42	=		*S 5.56*	=	**23.9**	× **Perigee**
22	23.45	+	0.91	=		*11.99*	=	**24.4**	
23	23.45	+	1.35	=		*17.82*	=	**24.8**	
24	23.44	+	1.72	=		*22.66*	=	**25.2**	
25	23.42	+	1.99	=		*26.18*	=	**25.4**	
26	23.39	+	2.13	=		*28.08*	=	**25.5**	
27	23.34	+	2.14	=		*28.23*	=	**25.5**	● **Spring tides**
28	23.31	+	2.03	=		*26.73*	=	**25.4**	
29	23.26	+	1.80	=		*23.79*	=	**25.1**	
30	23.20	+	1.50	=		*19.76*	=	**24.7**	
31	23.13	+	1.14	=	*7.6%*	*14.96*	=	**24.3**	
	S **Sun**		**Moon**						

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